ORNL/TM-2002/89

BUILDING ENCLOSURE HYGROTHERMAL PERFORMANCE STUDY Phase I

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Oak Ridge National Laboratory
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ACRONYMS

B.C.	British Columbia
BTC	ORNL Buildings Technology Center
BTESM	Building Thermal Envelope Systems and Materials
CCAB	Construction Codes Advisory Board
CMHC	Canada Mortgage and Housing Corporation
DCLU	Seattle Department of Design, Construction and Land Use
EIFS	Exterior Insulated Finish Systems
GSB	gypsum board
OSB	oriented strand board
Pa	Pascal
PVA	polyvinyl acetate
WSU	Washington State University

PREFACE

This report was produced by Dr. Karagiozis at the Oak Ridge National Laboratory in response to the City of Seattle's request to evaluate the hygrothermal performance of 35 wall systems in a climatic zone represented by the greater Seattle area. Three phases of work are designed to fulfill the full objectives of the project, with one phase evolving into the next. In Phase I, the relative performance of the 35 walls in terms of their hygrothermal response are examined based on existing information/knowledge of environmental loads, material properties, and system performance data. In Phase II, accurate material and subsystem performance data will be developed in laboratory conditions simulating field conditions. Finally, in Phase III, a series of field monitoring activities will demonstrate the performance of a few moisture-engineered wall systems. In Phase III, the monitored data will be used to further calibrate the advanced hygrothermal model and extend the performance data and add innovations to develop other low-energy durable wall systems. The overall objective of the complete project (Phase I, II, and III) is to develop moisture performance data and deliver a set of design guides for energy efficient and durable wall systems for the City of Seattle area.

This document reports only on the findings of Phase I, which seeks the preliminary assessment of the hygrothermal performance of walls in Seattle.

Three different sets of walls were simulated. The first set of walls is contemporary stucco-clad walls (19 walls); the second set is composed of two old stucco walls and a cedar-clad wall system (3 walls); and the third set is an assembly of nonstucco-clad walls (13 walls). Several variations of the basic wall systems were modeled, and the total number of simulations exceeded 35. Computer simulations were performed to analyze and develop the hygrothermal performance data for the selected walls. The purpose of Phase I was to develop the basic understanding of the complex heat and mass transfer processes occurring and to summarize the research performance findings from these selected walls in a form that is useful to building designers, installers, building code officials, and product manufacturers. The results presented in this report provide an evaluation of the relative performance of these wall systems. A newly developed ORNL framework for evaluating the hygrothermal performance of building envelopes was employed. This allowed a systematic ranking of the performance of the walls based on building science principles, rather than intuition only. The hygrothermal performance data for each series of walls were ranked independently using a mold-growth index. This approach is part of the innovative moisture engineering approach adopted in this work.

As with any simulation work, several system assumptions have been employed in this work. The assumptions are briefly described in this report.

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EXECUTIVE SUMMARY

Phase I of the City of Seattle Hygrothermal Building Envelope Performance Preliminary Analysis has been completed. Within Phase I, 35 walls were evaluated for their hygrothermal response to environmental loads present in the greater Seattle area. These wall systems were classified in three sets—a set of conventional stucco-clad walls, a set of pre-1984 stucco and cedar-siding walls, and a set of current nonstucco-clad walls. While all three classes were investigated, emphasis was placed on stucco-clad systems.

The selected walls were analyzed in terms of their hygrothermal performance and capability to handle moisture loads that are more in line with real conditions rather than ideal loads used in today's designs. For the first time ever, the concept of incidental water penetration was incorporated into the performance analysis of stucco-clad wall systems and nonstucco-clad wall systems for climatic conditions of Seattle. Several key moisture-design performance issues were investigated. In this report, pre-1984 walls are compared to post-1984 walls, and vented walls were compared to ventilated walls and walls with no ventilation. Walls were compared with different exterior sheathings and with different weather resistive barriers. This report examines the effect of increasing insulation levels, compares several different interior vapor control strategies, examines the effect of mechanical ventilation "negative pressures," and investigates the effects of interior humidity control in building envelopes.

The moisture performance of three different classes of wall systems has been investigated in the context of the preliminary hygrothermal analysis of walls in Seattle. The results reported in this phase specifically address the moisture performance of walls designed with loads that have some unintentional water penetration. The results have been developed in a manner to present the relative performance of the walls in the same climate with similar water penetration effects. The analysis was performed with the best available input data. Several limitations should be recognized within the context of this study.

The following findings are noted for the performance of the selected wall systems.

1. Results showed that selection of wooden sheathing boards on interior vapor-tight assemblies does not significantly influence the performance of stucco-clad walls. A larger effect was observed when the interior vapor control is made vapor open. When continuous cavity ventilation is employed, the effect of the selection of the sheathing board on the hygrothermal performance of the wall was found to be negligible.

2. When comparing oriented strand board sheathing performance against the performance of exterior grade gypsum, the differences are very significant in terms of the amount of moisture content present in the walls. Moisture content alone does not indicate their respective durability as durability is directly related to the combination of relative humidity and temperature, mechanical, chemical, and biological properties of the substrates. This study did not investigate the durability performance of either sheathing.

3. In terms of interior vapor control, inhabitant behavior must be considered during the wall hygrothermal design stage. If interior relative humidity is maintained below 60%, then a latex primer and paint may perform better than the use of polyvinyl acetate (PVA) or even a polyethylene sheet. When the interior environment is maintained at a higher relative humidity, then stricter vapor control is needed.

4. Multilayered building paper was experimentally shown to enhance the drainage capability of the stucco walls in a set of preliminary drainage tests. Water entry was found to be present in either dual- or single-layered systems, but single layers allowed substantially more water penetration.

5. The effectiveness of the building paper was found to depend on the type of vapor control strategy used on the interior. This connectivity is important to recognize. Results have shown that two layers of a 60-min paper system performed better than a single layer of No. 15 felt paper. In general, weather-resistive building papers play a very important role in a stucco-clad wall system. Vapor diffusion control is only one element of control these membranes offer.

6. Continuous venting of stucco walls provides a beneficial drying performance, which is not present in walls that are not vented. Continuous ventilating of stucco walls provides a further improvement in the drying performance of the stucco walls as compared to vented walls. The effectiveness of the weather-resistive barrier vapor diffusion control was found to be significantly smaller in the presence of ventilation, thus the choice of the weather-resistive membrane should be made for reasons other than vapor control.

7. Increasing the insulation levels from 89 mm to 140 mm or even 280 mm resulted in slightly higher moisture accumulation. Walls that have been designed with a more vapor-open interior showed negligible effects on moisture content accumulation caused by increased amounts of insulation applied to the walls. The limiting factor was establishing an acceptable interior environment, limiting the interior to 60% relative humidity.

8. The indoor environment plays a critical role for the performance of all wall systems. Increasing interior ventilation rates decreases the interior vapor pressure and relative humidity and enhances the performance of the stucco wall during different times of the year. The amount of ventilation required to reduce the interior relative humidity may be prohibitively large, and other means of dilunition by dehumidification may be beneficial when high interior moisture loads are present.

9. Operation of the mechanical system to provide .35 air changes per hour for at least 8 hours per day as required by the 1997 Washington State Ventilation and Indoor Air Quality Code caused increased moisture accumulation of the stucco-clad wall system. These code requirements may have contributed to increased moisture contents in the stucco wall systems, but it appears that mechanical ventilation merely acts to augment the existing significant air pressure differences caused by wind and stack effects. More testing is warranted to better understand the effects of mechanical ventilation on wall performance and durability.

10. Water penetration is the most critical influence on moisture management of wall systems. Neither vapor diffusion nor air leakage is comparable in magnitude. Water penetration may be several orders of magnitude greater than allowed by simple vapor or even liquid diffusion because of wind-driven rain. Water penetration at even a small fraction of the total rain load (1 to 2%) must be included in designs to represent realistic boundary conditions. The presence of windows and joints amplifies the local hygrothermal influences, as water loads become many times greater that in walls without windows and joints.

11. Exterior gypsum provides an additional resistance to both thermal and moisture flow that was found beneficial for a 2×4 old stucco wall arrangement. In this wall arrangement, concepts of “flow-through moisture control” seem to have very positive hygrothermal performances. At different times of the year, the conventional stucco wall displays higher amounts of moisture accumulation, while at the same time, allows more rapid drying. Cedar siding was found to permit a synchronized moisture performance with distinct moisture drying and wetting distributed during the year.

12. In all of the nonstucco claddings, the capability of the cladding systems to store water is limited in comparison to the stucco-clad cases. In most of these nonstucco-clad walls, a strong ventilation drying capability was present in the wall system. This ventilation factor reduced the available moisture in the wall components and limited moisture storage in the exterior cladding. This moisture performance resulted in walls that had less water stored in the critical elements of the wall.

1. Introduction

Controlling the accumulation of moisture in building enclosures has been a topic of growing interest, especially over the past 15 years. Immediately preceding that period, governmental and environmental concerns about conserving energy and customer demands for improving interior comfort led to the development of national standards and building codes requiring tighter building envelopes and increased insulation levels. The focus on improving the building envelope thermal performance has affected other aspects of building enclosure performance, most notably moisture performance. Experienced building scientists and professionals frequently share anecdotal evidence that as building enclosure tightness and insulation levels have increased over time, so have the number of premature building enclosure failures due to moisture accumulation. Older buildings simply do not fail at the same rate as newer buildings. Both old and new buildings experience moisture intrusion, but we do not fully understand what is causing newer buildings to incur moisture damage at a much faster rate than older buildings. Moisture accumulation seriously compromises not only the life span of building enclosures, but also negatively impacts indoor air quality and thermal performance.

In response to growing moisture damage problems in the Seattle area, members of Seattle's Construction Codes Advisory Board (CCAB)[1] began investigating moisture intrusion and damage problems in July 1998. Based on their experience, CCAB members have seen a disproportionate number of relatively new (built since 1984) multistory, multifamily residential structures experience premature building enclosure failures due to moisture accumulation. The CCAB established the moisture damage committee, an ad hoc committee of CCAB members, concerned state and local agencies, and community building professionals, to advise and guide CCAB's investigation of moisture damage issues. From November 1998 to March 1999, the Seattle Department of Design, Construction and Land Use (DCLU) and the moisture damage committee conducted an informal survey of multifamily residential structures in order to assess the approximate number of moisture-damaged structures in Seattle, the causes of moisture intrusion, and the cost to fix the damage. DCLU received 71 completed surveys representing 74 multifamily residential buildings constructed from the early 1900s to the mid-1990s. Two-thirds of the surveys represented structures built between 1984 and 1998. Fifty-one structures reported construction material and labor cost to repair these buildings; the total cost was approximately $98 million, not including the costs of investigation, attorneys' fees, or tenant/owner relocation costs.

As was found in the Vancouver, B.C., moisture damage surveys, interface details were listed as the primary source of water intrusion (CMHC 1996). The survey also found that moisture damage was not limited to exterior insulated finish systems (EIFS) clad walls, but affects all cladding types. Because participation in the survey was voluntary and surveys were sent to a small percentage of apartment owners and condominium associations, the survey results do not necessarily indicate increased moisture damage problems in newer multifamily buildings. However, the moisture damage committee members note that in addition to the 38 moisture-damaged structures for which they completed surveys, they have begun investigations into another 150–200 moisture-damaged structures in Seattle and the greater metropolitan area, most of which were built within the past 15 years. Based on DCLU permit tracking data, which shows that approximately 938 multifamily structures were built between 1984 and 1998, moisture damage appears to affect approximately 20 percent of the multifamily structures built in Seattle area over the past 15 years. After hearing presentations from Canadian building scientists and Oak Ridge National Laboratory (ORNL) Buildings Technology Center (BTC) staff, moisture damage committee

[1]The Construction Codes Advisory Board (CCAB) is the City of Seattle's advisory board for the technical construction codes. The CCAB comprises 13 members representing the construction industry, property owners, and the general public.

members recommended seeking moisture assistance from ORNL BTC staff in understanding factors that affect the hygrothermal performance of the western Washington/Seattle area building enclosures. DCLU agreed to provide funding to support the damage committee's study proposal, in addition to providing staff support. The Washington State University Cooperative Extension Energy Program (WSU Energy Program) agreed to be a partner in the research by providing library research services and technical support. The results of the research will be used by the state and local partners to develop technical guidance documents and, if necessary, proposals for code changes.

The strategy taken in this work was to refine and apply a moisture-engineering evaluation to develop engineering assessments that did not favor particular materials—claddings, insulation materials, weather resistive barriers or even vapor control strategy—but to examine the performance of the wall in terms of system/total moisture performance. The moisture performance of the walls was tracked in terms of its total hygrothermal response to thermal, moisture, and pressure loads.

Within the particular design of a building envelope, all kinds of considerations and priorities may exist. It is the purpose of this work to develop a better understanding of all processes affecting the performance of the wall. At the same time, an innovative approach on how an engineer/architect may apply a safety factor towards the design of a particular wall for hygrothermal loads will be demonstrated. This is a first attempt to employ such an analysis for moisture design of wall systems in Seattle.

To accomplish the overall tasks of the project requires implementation of all three phases. This report describes only the work conducted in Phase I which is the preliminary assessment of the hygrothermal walls in Seattle. Phase II seeks to develop a representative material property database and develop laboratory testing to characterize the wall system and subsystem effects. Finally, Phase III seeks to demonstrate and further improve the water management capabilities of wall systems by more field testing and modeling work.

1.1 PURPOSE OF SEATTLE WALL RESEARCH

The purpose of this research project was to assess

- the effect building enclosure components have on the transmission of heat and moisture into and out of western Washington/Seattle area building and
- the relative thermal efficiency and hygrothermal performance of older (pre-1984) western Washington/Seattle area building envelopes versus new (1999) building envelopes.

To accomplish the stated objectives, this project required state-of-the-art advanced computer modeling and expert consulting services from ORNL to study the predicted hygrothermal performance of the range of western Washington/Seattle area building enclosures.

The analysis sought scientific evidence to support or refute widely held beliefs regarding hygrothermal performance differences between older and newer structures and the role building, ventilation, and energy codes have played, if any, in affecting hygrothermal performance. The analysis also sought specific reasons for any differences that appeared and suggested improvements to Washington's residential construction codes.

1.2 VALUE OF ORNL RESEARCH ACTIVITIES

This research project complements ongoing activities in the ORNL BTC's Building Thermal Envelope Systems and Materials (BTESM) Program. It supports the Department of Energy's (DOE's) recently stated goal of developing long-term hygrothermal modeling capabilities and guidelines for moisture management strategies in wall systems. The understanding of how to construct thermally efficient and moisture tolerant residential building enclosures is already the main focus of the Moisture Technology Program at BTC (led by Karagiozis). The collaboration of Washington State University (WSU) Energy Program, moisture damage committee members, and DCLU staff supplied the needed historical and current construction code requirements and building details of western Washington/Seattle area structures. The ORNL program has the necessary expertise critical to the success of this research project. The principal investigator has been a leader in developing guidelines and handbooks for controlling moisture intrusion and accumulation using his expertise in analyzing and modeling hygrothermal performance.

2. RESEARCH APPROACH

2.1 CONCEPTUAL APPROACH FOR MOISTURE CONTROL AND DRYING POTENTIAL OF ENVELOPE SYSTEMS

Any wall system can be characterized as comprising a few basic subsystems. The exterior most subsystem is identified as the cladding or façade system. Others include the weather resistive barrier system, the sheathing system, the insulation system, the framing system, the vapor diffusion control system, and the air barrier system. A multitude of variations may exist among these fundamental systems. In some cases, the functions of several systems can be accomplished by one system if proper performance criteria can be satisfied. The drying capability of a building envelope system with initial construction moisture and recurring water penetration critically depends on the climatic conditions in which the wall is placed, and the system and subsystem performances of these wall systems and components. The drying rate mechanisms by which walls redistribute and transport moisture must be incorporated directly into the wall designs. When a wall is not properly designed with adequate drying capacity, the potential for moisture-induced damage significantly increases. The drying potential then becomes a distinct property of each wall system and can be ranked.

The design challenge is to develop building envelope designs that incorporate high drying potentials. This may be achieved by allowing the wall systems to dry towards both the outside and inside whenever possible. Several successful walls systems have been implemented for centuries that allow and control moisture flow using no restrictive elements. In the past such wall systems typically require a tremendous amount of energy to heat the space bounded by the walls. Today, the challenge is to design walls that include features to enhance energy efficiency.

In this section of the report, the moisture engineering approach developed at ORNL and detailed by Karagiozis (2001) is discussed. This approach was developed in a generic fashion and has been applied to other building envelope systems (Karagiozis 2001). As water is a solvent, all walls will eventually have water leaks. Some walls will leak as soon as they have been built while others may take a considerable time (heavy masonry systems). However, no matter how and why water penetrates through the wall, each wall has a distinct rate of drying. The drying rate of a wall depends on the loads to which the wall is exposed. The wall drying rate performance characteristic was used in this project, which is dependent not on one element but on all elements combined to assess the total hygrothermal performance. Subsequently, a wall ranking system was developed and used to rank the walls in terms of their efficiency in handling incidental water penetration.

Conventional moisture design of building envelopes essentially considers transport mechanisms due only to vapor diffusion. At best this conventional approach captures a very small portion of the possible “real moisture loads” in residential construction. Indeed, the loads present that are caused by air leakage may be 60–100 times those caused by vapor transport, while loads caused by wind-driven rain may contribute 10–100 times those caused by vapor transport. Walls in the past have been designed using models that were steady-state and material properties that were constant; and in almost all cases, they did not take into account the sorption capabilities of the materials. Rain, wind, solar, air and vapor pressure, and sky radiation were never used as driving potentials for moisture transport. Designs also assumed perfect systems—walls that never leaked air or water. These types of assumptions clearly illustrate the limitations of some existing and past design approaches, as the designs never included the “real” loads that actually dictate the moisture behavior of walls.

The approach adopted in this work is state-of-the-art. It includes contributions from hygrothermal loads caused by wind-driven rain, solar irradiation, sky radiation, mechanical pressures, wind-pressures, stack effect, vapor diffusion, liquid diffusion, sorption and suction storage, and temperature-dependent sorption capabilities. In addition, freezing, thawing, and evaporation-condensation characteristics were included in the analysis. At all times, the thermal transport was fully coupled to moisture transport.

In addition to these loads, the effect of water penetration was also included, based on the possible paths for water entry. The water penetration in the walls can be interpreted in two ways. It can be viewed as a possible construction/contractor index that is directly related to the level of workmanship or as an inherent feature of the wall. This inherent feature of the wall may represent the level of complexity in making the wall air tight or water tight. It may be related to the quality and durability of the materials involved. Materials and their associated mechanical, chemical, and hygrothermal properties may change as a function of time and the environment to which they are exposed.

For example, the enhancement in the evaluation approach used to assess the hygrothermal performance of stucco-clad systems recognizes that such walls need to resist more than just vapor diffusion loads. The stucco walls also need to resist influences of wind-driven rain, air leakage, and water penetration. This approach makes the results from this preliminary Phase I parametric study unique in North America and elsewhere.

In the simulation process, multiple levels of simulations were performed. Initially, a series of 1-D simulations was performed to develop basic performance understanding. This was followed by a series of 2-D simulations to further shed light on the performance characteristics of the walls. Finally, another set of advanced 1-D simulations was performed to focus on some of the dynamic performance attributes of the walls. To summarize these activities, Fig. 1 visually displays the simulation process required to develop performance characteristics of the walls.

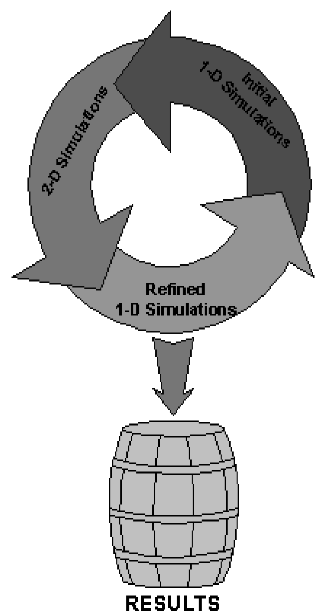

Fig. 1. Simulation analysis process.

The following tasks were required to achieve the objectives of Phase I of the project:

- identify building enclosure components to be researched as part of the project;
- use advanced computer models to predict the hygrothermal performance of the selected building wall enclosures;
- use computer modeling results to assist in identification of code-related factors affecting hygrothermal performance;
- document through research reports the results of ORNL’s participation in the research project; and
- present results at a meeting of WSU Energy Program and DCLU staff and a meeting of western Washington/Seattle area building professionals.

2.1.1 Literature Review: Relationship of This Work with Research at Other Locations

Stucco-cladding systems have been associated with several moisture-related problems. Canada Mortgage and Housing Corporation (CMHC) recently developed a best practice guide that details problems with stucco-clad system for wood-frame envelopes in the coastal climate of British Columbia (CMHC 1996). In a recent report by Onysko (2000), a series of walls was tested for laboratory drying conditions using vapor transmission concepts. In the past, some of these moisture problems have been solely attributed to vapor diffusion. The hypothesis was that after the inside surface temperature of the substrate sheathing was below the dew point of the interior air, the resulting condensation could expose the substrate sheathing to prolonged wetting. Wetting also occurs if rain penetrates to the substrate system or sheathing. Moisture transport by diffusion is not as powerful a means of moving vapor into a wall as air leakage, but it may act for a long time (i.e., the entire fall and winter). Insufficient vapor diffusion control can also cause interstitial condensation. Outward cold-weather diffusion can be a practical problem with stucco-clad systems. Moisture problems ranging from high moisture content in the exterior sheathing to total rotting were uncovered in houses that were occupied for as few as six months (Ricketts 1998). However, most of the catastrophic failures reported in B.C. were attributed to poor flashing details and the penetration of water into the wall systems. The problems developed because moisture did not dry out quickly enough. Questions have been raised about the effect of the interior vapor control strategy and the amount of insulation and air leakage on the drying of the walls.

Water entry into wall constructions can have consequences. Moisture entry into the wall structure can be caused by four transport processes: vapor diffusion, liquid diffusion, water leakage, and moist air leaking inward or outward through the building envelope. Moisture transport by diffusion occurs under the influence of vapor pressure or moisture content (capillary suction pressure) gradient. A detailed description of the literature in the area of vapor diffusion control has been presented elsewhere. Vapor retarders have been devised to control moisture flow by vapor diffusion into the wall structure. Vapor retarders are materials or systems which are designed and installed to control the transmission of water vapor across the wall assembly. The application, location, and selection of the vapor retarder is dependent on wall design and climatic conditions. Results showed that for weather conditions such as those in Vancouver, a coating of paint with a permeance as high as 400 $ng/(Pa \cdot m^2 \cdot s)$ may prevent harmful moisture accumulation caused by diffusion. A recent follow-up study demonstrated the importance of interior vapor control for the drying capabilities of a specific barrier EIFS-clad wall system in mixed climates such as found in Wilmington, North Carolina, because drying towards the exterior was limited with a barrier EIFS-clad wall system. The majority of other documented problems that result from either rain or condensation entering the wall cavity are associated with substrate sheathings that use paper-faced gypsum sheathing and oriented strand board. Water vapor in air that leaks into or through a wall can condense on cold surfaces and deposit significant amounts of moisture on the back of the substrate sheathing.

Exterior cladding with low vapor permeance can greatly reduce the potential for outward drying. A very low vapor permeance layer on the inside (e.g., polyethylene sheet) can also eliminate any practical amount of drying to the inside. In this situation, any water that does enter the wall has little or no chance to leave, and therefore moisture can accumulate. Computer simulations can be performed to develop appropriate specifications for the required level of vapor control for a particular wall and climatic condition. This research performs a dynamic analysis and will give guidance on the effect of interior vapor control strategies that should be used in climates like Seattle.

2.1.2 Air-Leakage Movement

A large fraction of the energy consumed for space heating is used to heat ventilation air. Residential buildings need to be ventilated with outdoor air to maintain acceptable indoor environments. Different ventilation schemes are implemented in buildings to provide the necessary ventilation and include balanced mechanical systems, natural ventilation, controlled ventilation, and exhaust-only ventilation systems. In the cases where ventilation is not controlled, air infiltrates or exfiltrates through the building envelope at unintentional openings around the sill plate, wall cracks, basement footing and first floor and at subsequent floor connections, plumbing stack, electrical service conduits, openings for heating and cooling ducts, and window/wall junctions. Infiltration can contribute significantly to the overall heating or cooling load of a building and is directly dependent on environmental loads, envelope design and operation, and construction workmanship. This kind of infiltration/exfiltration is common in residential buildings and influences the indoor air quality, building energy consumption, and durability of a building. In a recent publication Buchanan and Sherman (1998) note that a great deal of work has been devoted to the prediction and measurement of infiltration rates in building systems, but little effort has been directed toward determining the actual energy impact of infiltration.

To prevent and control possible air leakage through buildings, air barriers are employed that avert excess ventilation and the associated energy costs. Air leakage is essentially controlled by an air-barrier system, which is designed to limit moisture transport. Walls with condensation from air leakage have a failed air-barrier system. Air leakage can be a dominant factor in the transport of heat and moisture through building envelope systems. Deterioration of envelope systems can in many instances be attributed solely to moisture transported caused by air leakage.

In cold climates, the interior conditions normally produce higher vapor pressures during the winter period than those produced by the exterior. Depending on the effect of stack pressures, interior mechanical pressures, and wind pressures, positive or negative pressure differentials can exist between the inside and the outside of the envelope. The presence of pressure differentials drives quantities of air through intentional and unintentional openings (cracks). Depending on the temperature distribution and the air passage routes through and around the various material sections in the envelope, moist air can condense. This accumulation of moisture due to air leakage can be much more significant than the diffusion transport caused by vapor condensation. Experimental work detailing the air-flow paths within walls has not yet been developed, so information is generally lacking. Information regarding the hygrothermal performance of wall systems attributed to air leakage is limited for cold climates.

2.2 Simulation Activity

In this report, the ORNL research hygrothermal model MOISTURE-EXPERT version 1.0, developed by Karagiozis (2001), was used to parametrically investigate the moisture performance of the selected wall systems. The first wall set was composed of contemporary stucco-clad systems, the second set was composed of old stucco clad and old cedar-clad systems, and the third set was composed of contemporary nonstucco-clad systems.

For each of these walls, two or more water penetration rates, two different interior vapor environments, and two interior ventilation conditions (mechanical ventilation according to code or none) were investigated. The present work assessed the moisture engineering performance of certain wood frame envelope systems not only in terms of the development of temperature and relative humidity distributions, but also in terms of the risk for mold growth using results from ORNL's advanced hygrothermal modeling tool, MOISTURE-EXPERT.

A visual description of the level of inputs required is given in Fig. 2. The general required inputs to the model are as follows:

1. material properties,
2. exterior environmental loads,
3. interior environmental loads, and
4. envelope system and subsystem characteristics.

In input 4, envelope system and subsystem characteristics, Phase I of the project had to rely on expert advice and on some preliminary drainage tests performed at Building Science Corporation (details given

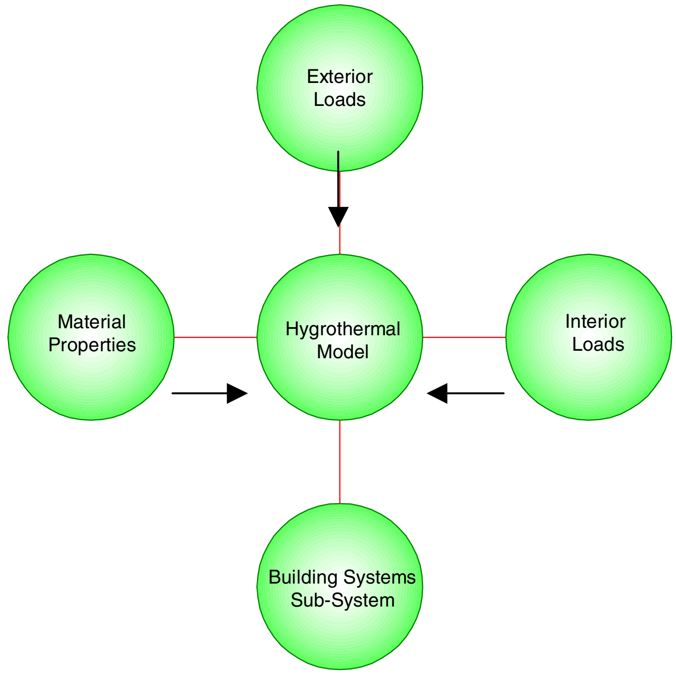

Fig. 2. Inputs required in 1-D and 2-D hygrothermal simulations.

in Appendix D). In the following sections, details are briefly given about these required inputs to the model. Approximately 6,000 inputs are required by the model for a 2-dimensional simulation.

2.3 Boundary Conditions and Initial Conditions

The analysis was conducted while subjecting the exterior boundary of the wall to actual weather data, which included temperature, vapor pressure, wind speed and orientation, solar radiation, wind-driven rain, sky radiation, and cloud indexes. Wind-driven rain water penetration was included in the analysis; the exterior surface was exposed to the amount of rain water that hits a vertical wall under wind conditions. A 10% percentile cold and 10% percentile hot year was developed for Seattle from 30 years of hourly data collected by the National Climatic Data Center. Two consecutive years of simulations were performed that included the 10% hot and 10 % cold years from the 30 years of data. The hourly solar radiation and long-wave radiation from the outer surfaces of the wall were also included in the analysis. This approach is currently being proposed by ASHRAE SPC 160P and is discussed by Treschel in the ASTM Manual 40 (ASTM 2001) and has been examined in detail by IEA Annex 24. All wall systems investigated in this paper were subjected to the same climatic conditions of Seattle, Washington.

Interior conditions were also allowed to vary depending on the time of day and exterior conditions and by adding additional moisture sources. Internal conditions were dynamic, and an hourly moisture generation schedule was implemented. As no air conditioning during the summer months was used, the temperatures were allowed to float above 21°C. The lower limit of relative humidity was set at 30% at which time the inhabitants were assumed to turn on humidification equipment. Figure 3 displays the interior relative humidity conditions for the two complete years beginning on July 1. The average relative humidity is approximately 48%, which corresponds to a representative interior. However, during the wet, rainy seasons, the interior relative humidity rises to as high as 70%. Figure 4 shows the solar radiation and precipitation for a 10% cold year and a 10% hot year.

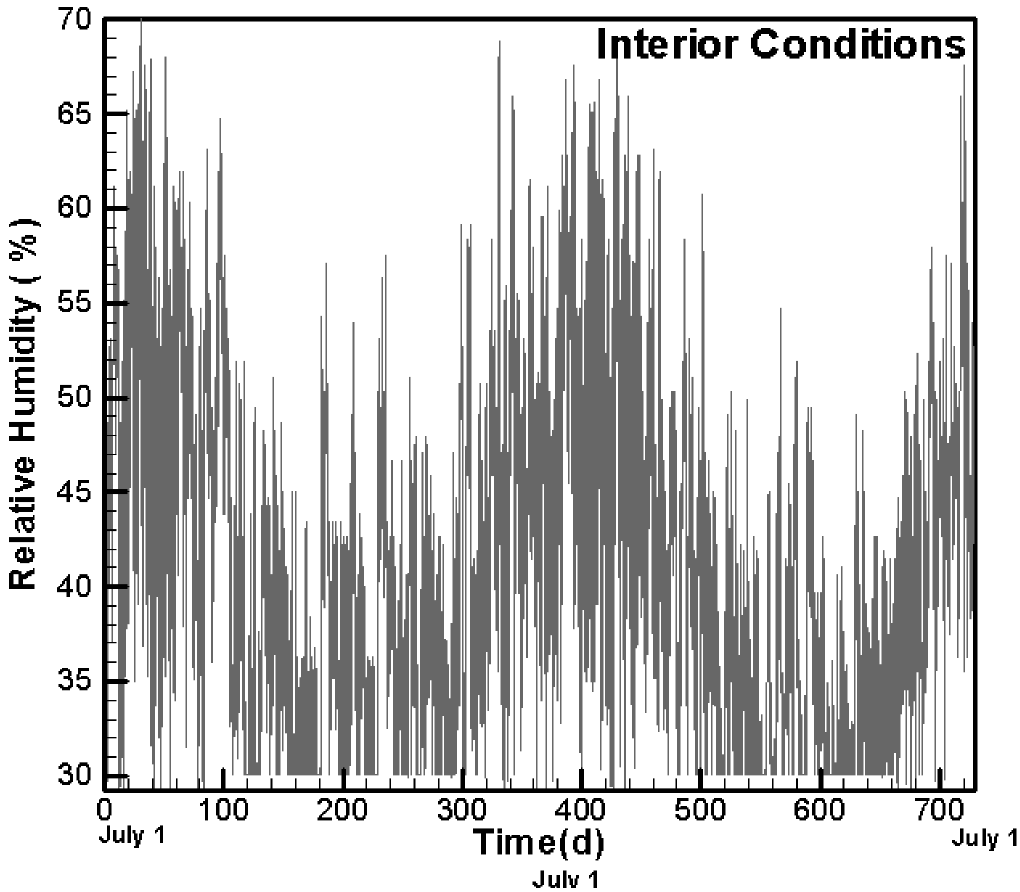

Fig. 3. Interior conditions (low RH conditions).

To investigate the influence of interior environmental loads, a series of field test were implement in which 12 residences were instrumented with HOBO-Pro Series temperature and relative humidity sensors. In most of these 12 residences, at least two locations were monitored. The results of this research activity to

determine the indoor air quality of the different residences will be reported elsewhere. Data from the field monitoring was used to develop the 24-h schedule used in the modeling activity. The resulting interior relative humidity is shown in Fig. 4. This represented a case of a family of four living in an apartment with 950 ft^2 area.

The modeled walls were assumed to be located on the second floor of the building. The walls were assumed to face south. The heat and mass transfer coefficients for external surfaces were assigned values that varied from hour to hour depending on the exterior weather, wind speed, and orientation conditions. Two water penetration scenarios were investigated. In the first scenario (RH-low), the initial conditions of the walls were assumed to be in moisture equilibrium at 85% relative humidity and water penetration was 2% of the amount of the water striking the exterior surface. In the second scenario (RH-high), the walls were initially at moisture equilibrium in a wet state of 98% relative humidity but with subsequent water penetration of 0.2% of the wind-driven rain component. Both scenarios represent conditions that correspond to differing levels of water protection of building materials offered in field conditions. The water penetration was deposited on the exterior sheathing, and, for this report, only oriented strand board or exterior-grade gypsum sheathing was used. As the objective of this study was to rank the walls with respect to the manner in which they handle incidental water penetration, the 1-D simulation did not include air mass transfer influences. The drying out performance of the walls was examined in terms of

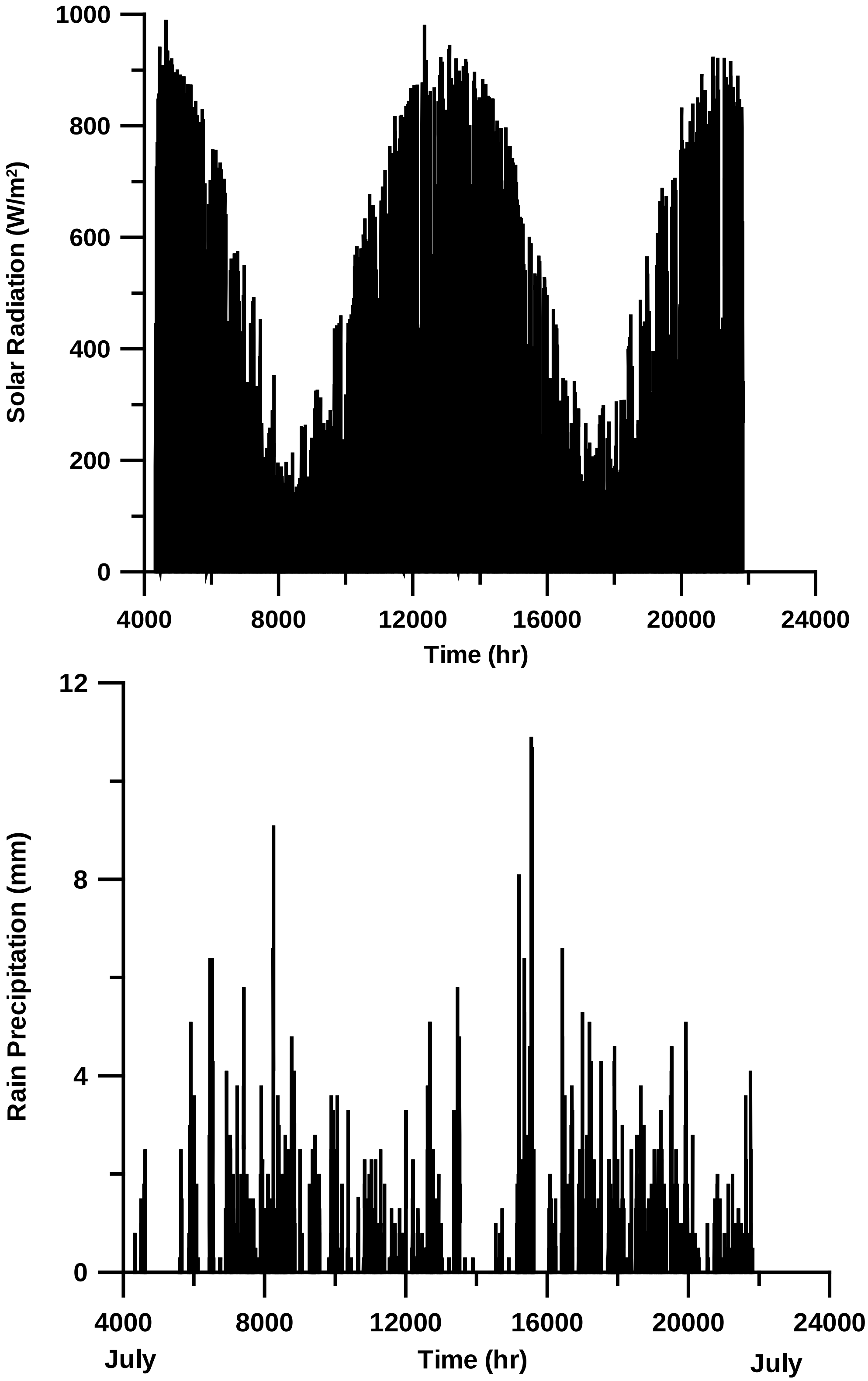

Fig. 4. Solar radiation and rain precipitation (July 1 = day 0, 10% cold year, 10% hot year).

vapor and liquid diffusion processes in the 1-D cases. Ventilation drying was also modeled for these cases. Drainage was also included in the wall systems, and different drainage capabilities were offered as a function of the type and placement of the weather-resistive barriers.

In the 2-D simulations, the combined effects of infiltration/exfiltration, the effects of mechanical pressure, the 2-D spatial effects, and the 2-D drainage effects were examined. The 1-D and 2-D simulations allowed a better understanding of the attributes of the effect of insulation, interior vapor control strategies, insulation placement, single- or double-weather resistive layers, and other variation on the total drying performance of building envelope parts.

2.4 Material Property

In this section some additional information is given on the particular moisture properties that are needed in advanced hygrothermal models.

2.4.1 Sorption Isotherms

Most building materials are hygroscopic, which means that they absorb water vapor from the environment until equilibrium is achieved. This behavior can be described by sorption curves over a humidity range between 0 and 95% RH. For some materials in which the equilibrium water content is not very sensitive to changes in temperature, the sorption curves are called sorption isotherms. Sorption curves and sorption isotherms for these materials from 95% RH up to the capillary saturation at 100% RH are difficult to measure. In this range, the equilibrium water content of a material is still a function of relative humidity. However, this function can no longer be determined by sorption tests in climatic chambers. Here, a pressure-plate apparatus is necessary to complete the sorption curve in the high-humidity range. The resulting water retention curve is a prerequisite for simulations, including liquid transport.

The sorption isotherms are the equilibrium moisture content states in a porous material as a function of relative humidity at a particular temperature. Families of sorption isotherms that encompass both the hygroscopic and capillary regimes are

- absorption isotherms,
- desorption isotherms,
- hysteresis isotherms (the equilibrium moisture content curves that span the complete spectrum of moisture equilibrium during both absorption or desorption), and
- temperature-dependent sorption curves (the equilibrium moisture content curves dependent on temperature).

The units for moisture content employed in the sorption isotherms are

- water content (kg/m^3),
- moisture content by mass (kg/kg), and
- moisture content by volume (m^3/m^3).

The hysteresis between absorption and desorption isotherms is usually not very pronounced. Rode (1990) approximated the effect of hysteresis and found that the effect on the calculated water content results was not large. Most models do not incorporate hysteresis and use the absorption isotherm or, where necessary, an average function of absorption and desorption. Figure 5 shows the combined sorption/suction isotherms. Neglecting the hysteresis might not have a great influence on the water content, but it dampens the fluctuations in relative humidity within the building assembly. In order to avoid this effect, separate absorption and desorption isotherms and a validated method to interpolate between both curves must be employed.

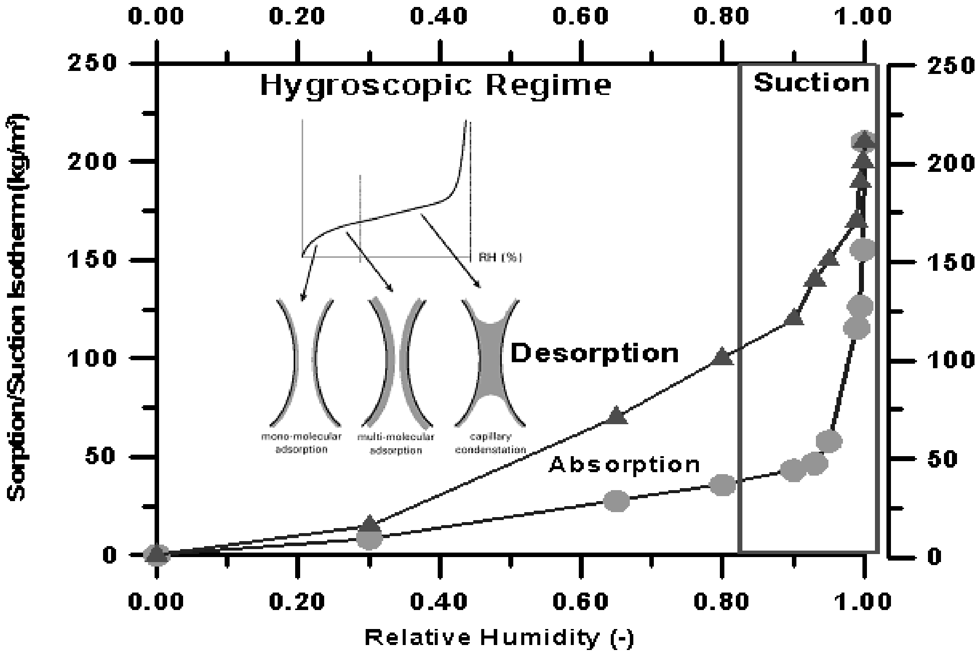

Fig. 5. Sorption/suction isotherm.

Nearly all advanced hygrothermal models with the exception of MOISTURE-EXPERT use a single curve to represent the absorption/desorption equilibrium isotherm. MOISTURE-EXPERT uses a set of sorption isotherms at different equilibrium temperatures. This is may be important when simulating wood-based material elements, and is probably less important for mineral-based materials.

2.4.2 Vapor Permeability

The vapor permeability [kg/(m·Pa·s)] is defined as the transport coefficient for vapor diffusion in a porous material subjected to a vapor pressure gradient and represents the mass transfer rate per unit length and pressure difference. In most technical publications, vapor permeance is reported as being used to characterize the vapor transmission coefficient. Vapor permeance [kg/(m^2·Pa·s)] is defined as the ratio between the vapor flow rate and the magnitude of vapor pressure difference across a slab in steady-state conditions. Other expressions for vapor permeability exist, such as the transport coefficient under a vapor concentration gradient (m^2/s) or as a vapor resistance factor, μ. To determine the vapor permeability of a porous material, the ASTM Standard E96 for water vapor transmission of materials may be used. It is important to recognize that the full dependency of the vapor transport coefficient as a function of temperature and relative humidity must be included in the model. In Fig. 6, the vapor permeability is shown for a vinyl film, and a strong functional dependency of the vapor permeability on relative humidity is displayed at 21°C.

2.4.3 Liquid Transport Properties

The coefficient that describes liquid flow is defined as the liquid transport coefficient. The liquid flux in the moisture transport equation is only slightly influenced by the temperature effect on the liquid viscosity and consequently on liquid transport coefficients. Most of the time, moisture diffusivity is used, which is the total diffusivity measured. Moisture diffusivity is used mainly because of the difficulty in determining

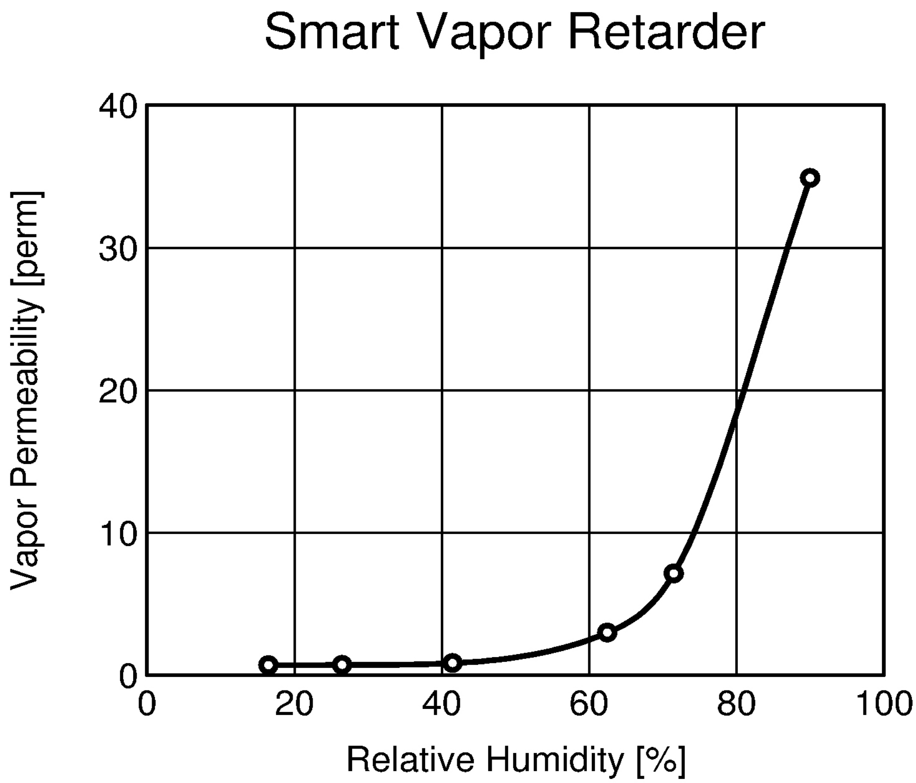

Fig. 6. Vapor permeability as a function of relative humidity.

what part is pure liquid flow and what is enhanced vapor flow. Different moisture-dependent liquid transport coefficients exist according to the transport potentials of the advanced models, and some are

- moisture diffusivity, Dw [m^2/s],
- liquid conduction coefficient, D_φ [(kg/ms)], and
- hydraulic conductivity, D_p [kg/(m·s·Pa)].

The transport coefficient for liquid flow can change dramatically from one time step to the next. Several order-of-magnitude changes occur in the transport coefficients when rain first strikes a building's exterior façade because of the steep increase of the diffusivity with water content. These large changes may cause numerical stability or convergence problems, and special numerical solution methods are required.

Künzel, Karagiozis, and Holm (2001), provide an explanation for the differences in diffusivity employed for the wetting and drying (liquid redistribution) process. Indeed, depending on the material, a factor of up to 10 or more may exist between these transport coefficients for the same water content. Only two of the advanced hygrothermal models include this discrimination for the liquid transport process by employing two distinct coefficients, WUFI and WUFI-ORNL/IBP and recently MOISTURE-EXPERT.

2.5 Directional Properties

Another important material property consideration in advanced hygrothermal models is that many materials exhibit very different behavior in the x, y, and z Cartesian directions. For example, moisture transport in wood is directionally dependent. Thermal properties may also be spatially dependent such as the thermal conductivity in fibrous materials, depending on the packing arrangement. For the advanced hygrothermal models that include air flow, the directional dependence of air permeability is also important.

The predictive accuracy of advanced hygrothermal models depend more on the realistic material properties than those used in simplified models. As more and more transport processes are included in a model, the errors from uncertainties in each process propagate further than in simple lumped models.

Currently, a need exists for developing material properties that are both more accurate and representative. Recent data from ORNL is state-of-the-art advanced hygrothermal property laboratory are expected to bridge this gap and provide information about the needed heat and moisture transport properties for a wide range of North American construction materials.

To summarize, information about the following material properties was gathered:

- water vapor permeance as a function of relative humidity;
- liquid diffusivity as a function of moisture content;
- sorption + suction isotherm as a function of temperature; and
- thermal conductivity, density, and heat capacity as a function of temperature and moisture content.

These properties are not single valued but may also depend on time, history, or other dependent variables. Directionally dependent material properties were employed for wood-based and insulation materials. Because the existence and reporting of basic material properties varied widely from manufacturer to manufacturer, the material properties employed in these simulations were taken from Künzel (1994), Künzel, Karagiozis, and Holm (2001), IEA Annex 24 (Kumaran 1996) and from the recent 2001 ASTM Manual 40 (ASTM 2001). In Appendix B, plots are provided for the material properties used in these simulations.

The MOISTURE-EXPERT model can handle internal heat and moisture sources, gravity-driven liquid moisture, and surface drainage capabilities. The model also captures experimentally determined system and subsystem performances and anomalies of the building envelope. One of the model's unique features is its capability to handle temperature-dependent sorption isotherms and directional- and process-dependent liquid diffusivity.

3. DESCRIPTION OF THE HYGROTHERMAL MODEL

3.1 MOISTURE-EXPERT MODEL

The MOISTURE-EXPERT hygrothermal model was developed at ORNL by Karagiozis (2001) and was used in this work. The model was developed to predict the dynamic 1-D and 2-D heat, air, and moisture transport in building envelope geometries. The model treats vapor and liquid transport separately. The moisture transport potentials are vapor pressure and relative humidity, and temperature for energy transport. The model includes the capability of handling temperature-dependent sorption isotherms and liquid transport properties as a function of drying or wetting processes.

The MOISTURE-EXPERT model accounts for the coupling between heat and moisture transport via diffusion and natural and forced convective air transport. Phase change mechanisms due to evaporation/condensation and freezing/thawing are incorporated in the model. The model includes the capability of handling internal heat and moisture sources, gravity-driven liquid moisture, and surface drainage capabilities. The model also captures experimentally determined system and subsystem performances and anomalies of the building envelope. One of the model's unique features is its capability to handle temperature-dependent sorption isotherms, water penetration, and directional- and process-dependent liquid diffusivity. For these wall simulations, a majority of the simulations were performed using the 1-D and enhanced 2-D version of the model.

The moisture transfer equation including contributions from liquid, vapor air flow, and gravity-assisted transfer is as follows:

$$\dot{m}_M = -D_\phi(u,T,x,y)\nabla\phi - \delta_p(u,T)\nabla P_v + v_a\rho_v + K(u)\rho_w\vec{g} \quad ,$$

where

$\dot{m}$ = mass flux, [kg/(m^2·s)],
ρ = dry density of porous material, kg/m^3,
Dϕ = liquid moisture transport coefficient, m^2/s,
u = moisture content, kgw/kgd,
T = temperature, °C,
δp = vapor permeability, [kg/(s·m·Pa)],
P_v = vapor pressure, Pa,
va = velocity of air, m/s,
ρv = density of vapor in the air, kg/m^3,
K = moisture permeability, s,
ρw = density of liquid water, kg/m^3,
g = acceleration due to gravity, m/s^2.

In Fig. 7, the simulation procedure is detailed for Phase I of the project. Information was supplied to the model that took into consideration system and subsystem effect and available expert knowledge.

3.2 MOLD-GROWTH MODEL

The essential ingredients required for the reproduction of molds are spores, adequate temperature, food source, and moisture. Mold growth in the building structures was estimated using a model equation that employs temperature, relative humidity, and exposure time as inputs. The mold-growth model and

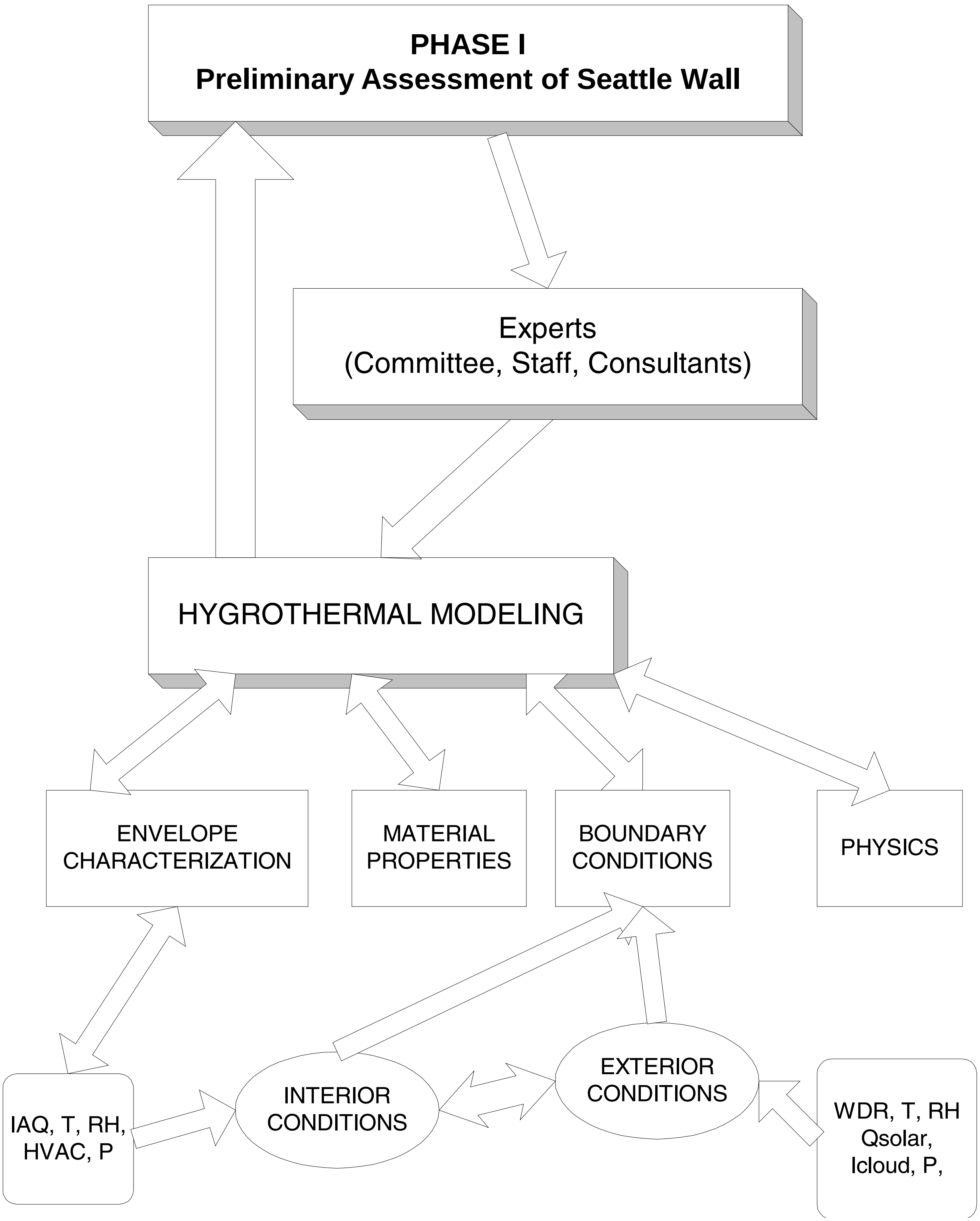

Fig. 7. Wall simulation approach using ORNL's MOISTURE-EXPERT.

differential mathematical equations were developed and presented in detail by Hukka and Viitanen (Hukka and Viitanen 1999; Viitanen 1997a; Viitanen 1997b), and only a short description is given here.

Quantification of mold growth in the model is based on the mold index first employed in biological experiments during visual inspection (Viitanen 1999). The mold-growth model is based on mathematical relations for the growth rate of mold index in different conditions, including the effects of exposure time, temperature, relative humidity, and dry interrupt periods. The model is purely mathematical in nature, and because mold growth was investigated with only visual inspection, it does not have any connection to the biology in the form of modeling the number of live cells. Also, the mold index resulting from computations with the model does not reflect the visual appearance of the surface under study because traces of mold growth remain on wood surface for a long time.

The correct way to interpret the results is that the mold index represents the possible activity of the mold fungi on the wood surface. The model makes it possible to calculate the development of mold growth on the surface of wooden samples exposed to fluctuating temperature and humidity conditions including dry periods. The numerical values of the parameters included in the model are fitted for pine and spruce sapwood. The details on the set of equations that are solved for each time step are presented in a paper by Viitanen, Ojanen, and Salonvaara (2000) at the BETEC Bugs, Mold and Rot III symposium. The authors recognize that it would be preferable to use a mold-growth index with numerical values fitted for wood species typically used Pacific Northwest wood-frame construction, but in the absence of such values, the functional form of the model can be reasoned to be valid also for other wood-based materials. It is important to note that the mold-growth index is not an absolute indicator of potential mold problems, but is a predictor of relative risk to aid designers in understanding the implications of their designs under different conditions.

4. WALL SYSTEMS

Thirty-five wall systems were employed in the parametric analysis. Tables 1a and 1b describe the contemporary stucco-clad walls, while Tables 2 and 3 describe the old stucco and the nonstucco wall respectively. In Appendix A, these walls are plotted. Essentially, the Seattle moisture committee selection was intended to allow

- comparison of pre-1984 wall to post-1984 walls;
- comparison of vented vs ventilated wall systems;
- comparison of different exterior sheathings;
- comparison of No.15 felt paper, 1-layer 60 min paper, 2-layer 60 min paper;
- comparison different vapor control strategies, including poly, kraft-faced batt, vapor-retarder paint, latex paint;
- examination of the effect of mechanical ventilation to show wall performance differences and, if possible, “negative pressure”; and
- discussion of the effect of interior humidity control in building envelope measures.

To provide insight to these intentions, a series of simulations were performed. Water penetration on the exterior side of the sheathing board was allowed at two levels, one at 2% of the exterior wind-driven rain and another at 0.2%. In this report, results are presented only for the case of the 2% water penetration.

4.1 ASSUMPTIONS

Several assumptions were implemented at different levels of the input parameters. Input parameters related to weather loads, interior moisture loads, material properties in which system and subsystem performance attributes were used. Assumptions were made that were consistent with the purpose of the project, which was to provide information about relative performances of walls in terms of their response to the same hygrothermal loads and inputs. The results from this project are termed “preliminary assessment results” as laid out by the original intent of the Seattle hygrothermal project. Subsequent phases of the Seattle project will develop more refined input data at each input level, and another set of iterative modeling simulations will be performed.

A few of the assumptions made are the following:

- Material properties used in the simulations are representative of material used in Seattle. Some of the material properties used may not have been measured from one sample, but rather several batches that included different manufacturers have been selected and matched. This method of material selection was used because these are the only material properties available at the present time.
- Weather data were developed from 30 years of hourly data by choosing the 10% percentile cold and hot years. This approach has been developed at IEA Annex 24 and has been used extensively in North America (ASHRAE is proposing this approach for SPC 160P).
- Water penetration loads used in the series of simulation are based on literature data mainly from water penetration around windows. Drainage performance was based on a report submitted to the City of Seattle conducted by Straube et al. (2001).
- Cavity ventilation rates were assumed. Experimental data are required to provide more quantitative validation data.
- Temperature dependencies were accounted for only in the wood top and bottom plates.
- System imperfections were not included other than water penetration

Table 1a. Contemporary stucco-clad walls
Post-1984 stucco exterior wall assemblies

	Exterior cladding 7/8 in cement stucco[1]			WRB[2]/ Drainage Plane						Exterior Sheathing				Wall Cavity						Interior Cladding and Finishing				
	Cement finish	Acrylic finish (Dryvit)	Silicon finish	15# Grade B felt[3]	60 min building paper[4]	2 layers 60 min building paper	19 mm air vented	19 mm air ventilated	50 mm air vented	½ in. plywood	½ in. OSB	½" GSB	Other	2×6 kiln dried hem-fir studs, 16 in. o.c.[5]	R-19 kraft-faced fiberglass batt	R-19 unfaced fiberglass batt	R-19 foil-faced fiberglass batt	R-11 unfaced fiberglass batt	½ in. rigid insulation (polyisocyanurate)	4 mil poly	5/8 in. Type X GWB	1 coat PVA primer	1 coat latex primer	1 coat latex paint
3A		X			X						X					X					X	X		X
3B		X			X					X						X					X	X		X
4A		X			X						X					X					X		X	X
4B		X			X					X						X					X		X	X
6A		X				X				X					X						X		X	X
6B		X				X				X						X				X	X		X	X
6C		X				X				X						X					X	X		X
8		X				X					X					X				X	X		X	X
9		X				X					X					X					X	X		X
14A		X		X							X					X				X	X		X	X
14B		X		X								X				X				X	X		X	X
15A[6]		X		X2			X1				X					X				X	X		X	X
15B[6]		X		X2			X1				X					X					X		X	X

[1]Stucco mix per ASTM standard (see NWCB Stucco handbook).
[2]Weatehr resistive barrier—asphalt-saturated building felt or building paper, or plastic housewrap.
[3]Manufacaturer and product: Fortifiber R-15.
[4]Manufacturer and product: Fortifiber Super Jumbo Tex.
[5]Moisure content = ≤10%.
[6]The wall has two weather resistive barriers, i.e., the air cavity and the building paper.

Table 1b. Contemporary stucco-clad walls

Post-1984 stucco exterior wall assemblies

	Exterior cladding 7/8 in cement stucco[1]			WRB[2]/ Drainage Plane						Exterior Sheathing				Wall Cavity						Interior Cladding and Finishing				
	Cement finish	Acrylic finish (Dryvit)	Silicon finish	15# Grade B felt[3]	60 min building paper[4]	2 layers 60 min building paper	19 mm air vented	19 mm air ventilated	50 mm air vented	½ in. plywood	½ in. OSB	½" GSB	Other	2×6 kiln dried hem-fir studs, 16 in. o.c.[5]	R-19 kraft-faced fiberglass batt	R-19 unfaced fiberglass batt	R-19 foil-faced fiberglass batt	R-11 unfaced fiberglass batt	½ in. rigid insulation (polyisocyanurate)	4 mil poly	5/8 in. Type X GWB	1 coat PVA primer	1 coat latex primer	1 coat latex paint
16A[6]		X			X2		X1				X					X					X		X	X
17A[6]		X			X2			X1			X					X					X		X	X
18A[6]		X			X2			X1			X					X					X		X	X
19A[6]		X			X2			X1		X						X					X		X	X

[1]Stucco mix per ASTM standard (see NWCB Stucco handbook).
[2]Weatehr resistive barrier—asphalt-saturated building felt or building paper, or plastic housewrap.
[3]Manufacaturer and product: Fortifiber R-15.
[4]Manufacturer and product: Fortifiber Super Jumbo Tex.
[5]Moisure content = ≤10%.
[6]The wall has two weather resistive barriers, i.e., the air cavity and the building paper.

Table 2. Old stucco-clad and cedar-clad walls

Typical pre-1984 exterior wall assembly

	Exterior cladding								WRB[1]			Exterior sheathing				Wall cavity				Interior cladding and finish			
	2 coats latex paint	7/8 in. stucco	Tniemscrete finish	1/8 in. cement finish	Vinyl siding	Aluminum siding	1 in. × 4 in. beveled cedar siding[2]	T-1-11 plywood siding, 5/8 in.	15# Grade B felt	Other	Other	5/8 in. GSB	½ in. plywood	None	Other	2×6^3 studs, 16 in. o.c.	2×4^4 studs, 16 in. o.c.	R-19 kraft-faced fiberglass batt	R-11 kraft faced fiberglass batt	5/8 in. Type X GWB	1 coat latex primer	1 coat latex paint	Other
2		X		X					X				X			X		X		X	X	X	
5							X		X				X			X		X		X	X	X	
6		X		X					X			X	X				X		X	X	X	X	

[1]Weather-resistive barrier.

[2]3/4 in. × 3-1/2 in. nominal dimensions.

[3]1-3/4 in. × 5-1/2 in. nominal dimensions.

[4]1-3/4 in. × 3-1/2 in. nominal dimensions.

Table 3. Contemporary nonstucco walls

Post-1984 exterior wall assembly

	Exterior cladding				WRB[1]/drainage plane							Exterior sheathing				Wall cavity				Interior cladding and finish				
	Vinyl siding	Galvanized metal	T-111	Hardiplank	½ in. air space	25 mm air space	7/8 in. foil-faced Isoboard[2]	15# Grade B felt[3]	2 layer 15# B felt	60 min building paper[4]	2 layers 60 min building paper	Dens-Glass Gold	5/8 in. Type X GSB	½ in. plywood	½ in. OSB	2 × 6 kiln dried hem-fir studs, 16 in. o.c.[5]	R-19 kraft-faced fiberglass batt	R-19 unfaced fiberglass batt	R-19 foil-faced fiberglass batt	4 mil poly	5/8 in. Type X GWB	1 coat PVA primer	1 coat latex primer	1 coat latex paint
1	X									X			X		X	X		X		X	X		X	X
2	X									X			X	X		X		X		X	X		X	X
3	X						X						X			X		X		X	X		X	X
4		X			X					X		X		X		X		X		X	X		X	X
5		X			X					X			X		X	X		X		X	X		X	X
6		X			X					X		X			X	X		X		X	X		X	X
7		X			X					X			X	X		X		X		X	X		X	X
8				X		X				X				X	X	X		X		X	X		X	X
9				X	X			X					X	X		X		X			X		X	X
10			X							X			X			X		X		X	X		X	X
11			X							X			X			X	X				X		X	X
12				X						X			X			X		X		X	X		X	X
13				X						X			X			X	X				X		X	X

[1]Weather-resistive barrier.
[2]Manufactured by Celotex.
[3]Manufacturer and product: Fortifiber R-15.
[4]Manufacturer and product: Fortifiber Super Jumbo Tex.
[5]Initial Moisture content = 25%.

- Air mass transfer was not included because Seattle exhibits little moisture accumulation due to this transport mechanism. Exceptions are discussed appropriately within this report.
- In this project, the effect of ageing of materials was not included due to the lack of data. Therefore, durability changes and influences were not included in this project.

With any engineering analysis, the loads used are assumed to be substantially higher than those expected in real systems. While this statement is not absolute, and exceptions may exist, nevertheless imposing higher than normal hygrothermal loads and tracking the performance of the walls to these loads is one way to design systems with an added safety factor.

In Phases II and III of the project, data will be generated to reduce the level of assumptions used in the preparation of the inputs. After inputs are generated, another series of simulations will be performed in both Phases II and III.

5. SIMULATION RESULTS

A series of simulations were performed as discussed previously. The response of walls was investigated in terms of how they managed high initial-construction moisture followed by repetitive incidents of water penetration, only a fraction of which was from water striking the wall. Water penetration was included so that the ingress of water would simulate exterior environmental conditions. A series of preliminary water drainage tests performed at the Building Science Corporation indicated that water penetrated through the weather-resistive layers and came in contact with the sheathing board. Preliminary quantification of water penetration ranged between 0.01% to more than 4% of the amount of water applied to the test panels. For example, in the simulation set that employed 2% water penetration, the value of 2% of the water was not the amount of horizontal precipitation but the amount of wind-driven rain striking the exterior envelope during the rain spell. As another example, if 10 mm of rain hit the exterior of a south-facing wall, 2% (only 0.2 mm) of that water penetration came in contact with oriented strand board (OSB) exterior sheathing board. During the simulation, each time that the exterior façade came in contact with wind-driven rain, 2% of that rain water was distributed as water penetration on the sheathing board. This is not the amount that diffused through the opaque portion of the wall but an amount of water that may have originated through cracks, penetration openings, joints, and window-wall interfaces. Indeed, this innovative moisture engineering approach for characterizing the hygrothermal performance may be envisioned as assigning a level of workmanship for a particular building envelope system or assigning an inherent water penetration index of the wall. The purpose of the simulation exercise was to determine the relative performance and ranking for drying among these wall systems subjected to either dry or wet initial conditions and/or high or low water penetration. This approach was implemented in order to mimic conditions close to reality.

5.1 PRELIMINARY SETS OF SIMULATIONS

To investigate the hygrothermal performance of the walls selected, many parametric simulations were performed. The first series of simulations was performed using interior moisture loads that included hygrothermal influences from inhabitants (moisture production), such as cooking, cleaning, and bathing. Moisture load values of each of these activities came from the Fundamentals Handbook from ASHRAE, IEA Annex 24 (ASHRAE 2001) and the ASTM Moisture Control Handbook 18 (ASTM 1994). A family of 4 (2 adults and 2 children) were assumed living in an apartment size of 800 ft^2. A complete series of 1-D and 2-D simulations were performed, analyzed, and presented to the moisture committee in early 2001. In these simulation cases, the resulting interior moisture conditions were found to be very high, and the respective performance of the walls to such high-moisture interior conditions led to a set of recommendations that may not have been necessarily ones that would be applicable to all buildings in Seattle. As a parallel activity, a series of HOBO Pro Series temperature and relativity humidity sensors were supplied by ORNL and a subsequent second series supplied by DCLU, which were used in 12 buildings. These instruments will measure interior conditions for one and a half years. A preliminary analysis of the indoor data showed that the interior moisture design loads used in the first series of moisture simulation were unacceptably high. As a result, another series of simulations were performed in May 2001, and these have been further refined by a third set in June 2001.

At the same time, a new moisture engineering approach implemented at ORNL become available for use in June 2001. This engineering framework was adopted for this project, allowing the project to extend the applicability of the preliminary set of simulations with better environmental loads. This exceeded the expectations and deliverables of Phase I of the project, as it already coupled some of the interior loads with field data results. Although all results presented in this report are preliminary, the refined approach, the preliminary drainage tests, and the indoor load monitoring have allowed better quality inputs to the simulation model.

Following are results that describe the performance of the walls with respect to the initially posed performance questions and issues. All figures illustrating performance are in Appendix C.

5.2 Post 84-Stucco Cases: Initial Conditions of 85% RH and 2% Water Penetration

5.2.1 Effect of Sheathing Substrate

In Fig. C1, the effect of sheathing substrate is shown for Case 3A (OSB) and 3B (plywood) for the performance of the whole wall. The y-axis depicts the total moisture content in units of kilograms per unit meter length and the x-axis time in days for a period of two years. The effect of either OSB or plywood is not significant in terms of overall performance of a wall with vapor-tight interior finishing [interior polyvinyl acetate (PVA) paint and latex paint]. However a net yearly moisture accumulation does occur. In Fig. C2, the transient moisture content of the sheathing board is shown for the same walls. The diurnal seasonal influences are more pronounced at the sheathing layers than at the whole-wall level. Figure C3, compares the OSB and plywood performance for the wall cases that included ventilation. These walls are cases 17A and 19A. For both of these cases, ventilation-assisted drying and wetting has a beneficial influence on moisture accumulation in the sheathing boards, but very small differences are observed in the two sheathings. Figure C4 compares cases 4A and 4B, both of which have a more open interior control strategy for vapor that uses a latex primer and paint. Results show larger differences (10%) between the two sheathing boards, indicating that sheathing substrate causes a larger effect when a more vapor-open interior control strategy is adopted. However, when comparing Figs. C2 and C4, results show that the sheathing boards do not store as much moisture when more vapor-open strategies are chosen. Figure C5 shows the influence of using either OSB or exterior grade gypsum board (GSB) as a sheathing substrate (cases 14A and 14B). The exterior grade gypsum board does not store large quantities of water, but this may be due to two factors: (1) material property data might not be representative or (2) the storage and release capabilities a vapor-open and high-liquid transport material may provide beneficial behavior.

Summary
With mild initial conditions, but incorporating a 2% water penetration into the wall, results show that selection of sheathing boards on interior vapor-tight assemblies do not significantly influence the performance of the wall. A larger effect is observed when the interior vapor control is made vapor open. When employing ventilation, the effect of board selection is negligible, but the walls also accumulate the least amount of water. However, when comparing OSB against the performance of exterior grade gypsum, the differences are very significant in terms of moisture content. At this stage of reporting, this does not imply anything with respect to durable performance as it is directly related to the combination of relative humidity and temperature, mechanical, chemical, and biological properties of the substrates.

5.2.2 Effect of Building Interior Vapor Control Strategy

In Fig. C6, the effect of interior vapor-control strategy is shown for wall cases 8 and 9. In case 8, a polyethylene vapor retarder was used in addition to the latex primer and paint, while in case 9 only PVA and latex paint was used. Both walls had two layers of 60-min building paper installed on the exterior. The walls' drainage capability was improved with the use of two layers of 60-min building paper. This allowed less water to be stored on the surfaces of the building paper for moisture diffusion or evaporation. The results clearly depict the detrimental effect of the use of polyethylene as an interior vapor-control strategy when interior relative humidity is kept within a healthy range of 30–60%. Wall 9 performed best in terms of moisture control. Figure C7 shows transient moisture content profiles for wall cases 3A and 4A. Comparing Figs. C6 and C7 shows a similar behavior. A parallel set of simulations were performed, where high interior relative humidities (yearly average of 65 and 70% RH) were employed. The results clearly depict the importance of interior vapor control and strongly suggest the benefit of using a low vapor permanence system.

Summary
Interior vapor control systems are important and must be designed using inhabitant information. If the relative humidities are maintained below 60%, then a latex primer and paint may perform better than the use of PVA or even a polyethylene sheet. When the interior environment is maintained at higher relative humidities, then stricter vapor control is required.

5.2.3 Effect of Building Paper Type (Weather Resistive Membrane)

Figure C8 shows the comparison of the use of a single- vs multiple-layer building paper using wall cases 3A and 9. The moisture performance is shown for the OSB layer. The primary enhancement shown for wall 9 was due to the better performing drainage. The additional vapor resistance of the building paper did not significantly affect the drying performance of the wall. The effective OSB sheathing board vapor resistance was several times higher, providing a limiting value for drying out. Figure C9 shows the moisture performance of the OSB sheathing board as a function of time for cases 8 and 14A. Here the effect of two different weather-resistive layers was evaluated: two layers of 60-min paper for case 8 and one layer of No.15 felt paper for case 14A. The results show that the lower vapor permeance at low relative humidities and the higher vapor permeance had a negative effect on the wall-drying performance of case 14A. At low relative humidities, the No.15 building paper is quite impermeable, making any kind of vapor diffusion through it very slow. However at high relative humidities (80% RH), the building paper behaves in an opposite fashion; it opens up and augments the vapor transmission.

Summary
Multilayered building paper was experimentally shown in a set of preliminary drainage tests to enhance the drainage capability of the stucco walls. The simulation results indicate the beneficial influence of such an arrangement with respect to changing exterior environmental conditions. The effectiveness of the building paper depends on the type of vapor control strategy being used on the interior. The results have shown that two layers of 60-min paper performed better than a single layer of No.15 felt paper. In general, weather-resistive building papers play a very important role in a stucco-clad wall system. Vapor diffusion control is only part of what these membranes offer.

5.2.4 Effect of Continuous Air Cavity Vents or Ventilation

In Fig. C10, the vented vs the nonvented case is shown for walls 14A and 15A. In this figure the total OSB moisture content is displayed for a period of two years. The benefits of venting (opening only at bottom) are clearly displayed. As venting provides a small fraction of the air exchange that ventilation (opening at bottom and top) may provide, it does provide some additional drying potential for these stucco-clad systems. The positive effect seems to be more beneficial during the 10% warm year (second year of simulation), indicating that the average relative humidity may be lower and as such may provide higher drying potential. Figure C11 displays the effect of a vented air space on wall cases 15B and 16A. These walls both have a vapor-open latex primer and paint on the interior surface; they employ a 19-mm air space gap but use different weather-resistive barriers as building paper, case 15B employs No.15 felt paper while case 16A uses 60-min paper. Figure C11 display the transient OSB total moisture content as a function of time. Results show that the differences between these two walls are small. During venting, the weather resistive barrier plays a lesser role in the overall drying potential of the wall. In Fig. C12, the effect of venting vs ventilation is shown for cases 16A and 17A respectively. Both walls employed 60-min paper and a 19-mm air-space gap. Results show that ventilation provides significant drying performance of the wall in comparison to just venting. To understand the influence of ventilation, a parametric analysis was performed on case 17A that varied the amount of air changes per hour in the ventilation air gap by 0.1, 0.5, 1, 5, 40, and 100 ACH. Figure C13 displays the total moisture content distribution due to ventilation for wall 17A. The air cavities that allowed more than five air changes per hour provided significant drying potential for the sheathing board of the stucco walls. The exterior water penetration load of 2% wind-driven rain can be successfully handled by having sufficient air change in the cavities. The average relative humidity in the sheathing boards is lower than 85% when sufficient cavity ventilation is present.

Summary

Venting stucco walls provides a beneficial drying performance over walls that are not vented. Ventilating stucco walls provides a further improvement in the drying performance of the stucco walls over vented walls. The effect of weather-resistive barrier vapor diffusion is significantly smaller in the presence of ventilation, thus the choice of weather-resistive barrier should be for reasons other than vapor control.

5.2.5 Effect of Interior Cavity Insulation Levels

In Fig. C14, results are shown for wall 4A with three different levels of interior insulation—89 mm, 140 mm, and 280 mm. There is minor influence of the level of thermal control on the moisture storage behavior of the exterior sheathing board. All walls regardless of the insulation level followed the same wetting and drying trends, with slightly higher accumulation for thicker levels of insulation.

In Fig. C15, the effect of adding insulation to wall 14A is shown. In this wall, a No. 15 felt paper is used as a weather-resistive barrier and a polyethylene film is used for interior vapor control. The results show that this wall is very insensitive to the level of insulation applied to the wall. Figure C16 shows results for the same three insulation levels but applied to wall 17A. This wall incorporates a vapor-open latex primer and paint for the interior and an exterior air cavity. Allowing vapor diffusion to dry out either towards the interior or the exterior minimizes the influence of higher insulation levels.

Summary

Increasing the insulation levels from 89 mm to 140 mm or even 280 mm allowed slightly higher moisture accumulation. Walls that have been designed to be more vapor open at the interior showed negligible effects on moisture content accumulation from adding more insulation.

5.2.6 Effect of Interior Environmental Conditions

The drying and wetting potential of a building is directly related to the loads provided by the exterior and interior environments. The influence of the interior environment is critical to the performance of the stucco walls. In Fig. C17, for Seattle exterior outdoor winter conditions at 5°C and 80% RH, results are shown for the influence of ventilation rates (air changes per hour) and moisture production rates on the indoor relative humidity conditions. In Fig. C18, the effect of ventilation on the yearly interior relative humidity is displayed. A moisture production rate of 10 kg/day was used, with three air changes per hour and an apartment area of 800 ft^2. In Fig. C19, the effect of ventilation on the yearly interior relative humidity is displayed using the same conditions as with Fig. C18, but with 0.3 air changes per hour. It is evident that within the greater Seattle area, ventilation alone is not necessarily the optimum method for reducing the indoor relative humidity. Even under these winter conditions, large ventilation rates are required to reduce the interior relative humidity to levels below 50%.

Several sets of simulations were performed to determine the interior loads in the simulations. Initially, inhabitant loads developed large periods of the year where the relative humidity was above 70%. Data analysis was performed on monitored temperature and relative humidity data and equivalent moisture production rates were calculated. These values gave time-dependent relative humidity percentages that were only a few hours per year above the 70% relative humidity threshold. An upper threshold of 70% RH was used in all the simulations, except in those that were parametrically varied. The moisture production of the inhabitants influenced the interior relative humidity in the simulations by a maximum of 14%. In Fig. C20, wall 4A is shown using different moisture-production rates. A lower limit (not feasible) is shown as the "no indoor moisture" case. The moisture production (kg/h) in that case corresponds to 0. The case that is depicted with a cross is the case that was used for all the simulations. Two other cases are plotted, a high case and a low case, corresponding to cases with different interior moisture-production rates or ventilation conditions. Figure C20 shows that indoor conditions dramatically influence the performance of the stucco wall. In Fig. C21, the effect of airflow and vapor control is simulated in 2-D for the high and low relative humidity cases.

Summary

The indoor environment plays a critical role for these simulations. Increasing ventilation rates decreases the interior vapor pressure and relative humidity and enhances the performance of the stucco wall. The amount of ventilation required to reduce the interior relative humidity may be prohibitively large, and other means of dilution by dehumidification may be beneficial.

5.2.7 Effect of Mechanical Ventilation

The Seattle moisture committee members hypothesized that the interior units of most Seattle area multifamily buildings are typically negatively pressurized relative to the exterior environment because of the exhaust ventilation strategies employed in most buildings to meet the ventilation requirements of the Washington State Ventilation and Indoor Air Quality Code. Based on field observations, moisture committee members hypothesized that this negative pressure is literally sucking exterior moisture into walls, thus contributing to premature envelope failure. A search of the literature for data quantifying the degree of negative pressurization revealed an analysis of innovative multifamily ventilation systems by Heller (1992), which reported "added pressure drops of 1–3.5 Pa across the envelope, typically enough to reverse the flow of air in the highest (air) leaks so that the entire (two-story) building was under negative pressure (while the mechanical system operated)." A study by Francisco and Palmiter (1996) of ten single-family homes reached a similar conclusion, but the authors noted that pressures caused by stack and wind effects were significant. The value of mechanical pressure used in the computer simulations, –1.2 Pa, was provided to ORNL from calculations by a moisture committee member and the report by Heller (1992).

In Fig. C22, the transient total moisture content (kg/m) in the OSB is plotted as a function of time for both the mechanical ventilation and for a no mechanical ventilation case. These two cases represent conditions that are intended to correspond to new and old code requirements. The current Seattle mechanical code requires that the mechanical system operates at least 8 h per day, while the pre-1984 Seattle mechanical code did not require mechanical ventilation. As the mechanical system operates, it was assumed to negatively pressurize the interior space for a period of 8 h per day. It is important to note that due to stack and wind effects, positive and negative pressure differentials between the interior and exterior environments varied throughout each day. Over the course of a year, taking into account the combined effects of mechanical ventilation and wind and stack effects, the south wall was calculated to be under a negative pressure (infiltration) 55% of the time, and a positive pressure (exfiltration) 45% of the time. A normal wind on the south face would contribute a positive pressure on the exterior face of the wall that could be enhanced during mechanical system operation, thereby increasing infiltration. At the same time, the north wall would see a negative exterior pressure that could have resulted in air exfiltrating the north wall system. The results shown here demonstrate the simulated effects of mechanical ventilation on the hygrothermal performance of a stucco-clad wall system (14A) and show that mechanical ventilation has the potential to enhance existing wind and stack effects which can be significant. Thus, mechanical pressurization is an important consideration as pressure differences drive moisture to accumulate within the building envelope.

Summary

The action of the operation of the mechanical system showed increased moisture accumulation of the stucco-clad wall system on the south side of a building during mechanical system operation. The current ventilation code requirements may have contributed to increased moisture contents in the stucco wall systems, but it appears that mechanical ventilation merely acts to augment the existing significant pressure differences caused by wind and stack effects. More testing of the actual pressure differences encountered is needed, as well as testing of air tightness for typical Seattle constructions in order to accurately gauge the range of effects mechanical ventilation may have on pressure differences across the building envelope. In addition, though mechanical ventilation was projected to increase moisture accumulation in the building envelope, the amount of additional moisture accumulated was within the capability of this wall to safely absorb and redistribute, allowing it to dry out. This, however, may not be the case for differently designed wall system.

5.2.8 Effect of Water Penetration

In Fig. C23, the effect of water penetration on the hygrothermal performance of the OSB sheathing board is shown for an airtight wall assembly. The total amount of moisture in the OSB layer per meter depth (kg/m) present in the wall system as a function of time is presented to show the relative hygrothermal performance of the stucco wall system for the five different levels of unintentional water entry. Results are displayed for the transient moisture content profile of the OSB layers. This part of the wall is the most sensitive part because the water was distributed at the exterior most surface of the wall. The wall system that was exposed to the largest water penetration, the 10% penetration case, displayed the slowest drying. Indeed, Fig. C23 indicates that this particular wall may exhibit acceptable hygrothermal performance only if water penetration is 1% or less. The wall with the lowest water penetrations exhibited the fastest drying potential, 0% and 1%. From the transient moisture content distributions for ideal conditions where the wall was not exposed to either wind-driven rain or water penetration, the wall showed an inherent ability to dry out. The differences between the “perfect” 0% penetration wall system and the “real” (all other wall cases) are significant.

In Fig. C24, the additional influence of the presence of a window is shown. Here, the effect of water run-off amplifies the effect of water penetration as the amount of water available is many times greater (6 times for this case). It is evident that in the areas underneath windows, flashing details, and unintentional openings are critical.

Summary

Water penetration is the most critical influence on water management of wall systems. Moisture loads may be several times greater than simple vapor and liquid diffusion with wind-driven rain. Water penetration at even a small fraction of the total load must be included in designs to represent realistic boundary conditions. The presence of windows amplifies the local influence, as water loads multiply by several times over those in areas without windows.

5.3 Pre-84 Stucco Cases and Cedar Case: Initial Conditions of 85% RH and 2% Water Penetration

Three wall systems shown in Table 2 were used for the pre-84 simulations. In these simulations, several additional assumptions were made, pertaining especially to the material properties of the stucco. Case 2 and 6 were stucco-clad wall systems, but without the acrylic stucco layer. Case 2 used a 2×6 wood frame construction, while case 6 used a 2×4 frame construction with exterior gypsum sheathing covering the plywood. Both walls used No.15 felt paper as a weather-resistive barrier.

Results comparing cases 2 and 6 are shown in Figs. C25 and C26 respectively. While the comparison is not that straightforward in terms of parametric differences (i.e., wall 2 is 2×6 while wall 6 is 2×4 and has an exterior gypsum sheathing that covers the plywood) results show that wall 6 accumulates significantly less moisture as a function of exterior climatic conditions.

Figure C27 displays a comparison of a current stucco wall and the pre-84 walls. Again, a direct comparison cannot be made; however, the results indicate that case 6 old stucco outperformed case 2 and the contemporary stucco wall cases. Case 4B showed higher seasonal fluctuations than the other walls. Case 4B also showed a greater sensitivity to the 10% warmer year (second year of the graph) than the 10% colder year (first year on the graph).

Figure C28 shows the comparison of all pre-84 wall systems. The transient moisture of the plywood is displayed for the two pre-84 stucco cases and those for the cedar siding. The cedar siding shows a distinct behavior with distinguishable seasonal moisture release and accumulation cycles. The performance of wall 6 remains the one with lower moisture accumulation.

Summary

Exterior gypsum provides an additional resistance to both thermal and moisture flow that is beneficial for a 2×4 wall configuration. In this wall arrangement, flow through moisture control seems to have very positive hygrothermal performances. The conventional stucco wall at times shows higher amounts of moisture accumulation, but at the same time, it allows more rapid drying. Cedar siding permits a synchronized moisture performance with distinct moisture drying and wetting distributed during the year.

5.4 NONSTUCCO CASES: INITIAL CONDITIONS OF 85% RH AND 2% WATER PENETRATION

Thirteen wall systems were initially included in this part of the study, as shown in Table 3. However, data discriminating the hygrothermal material properties of a few materials listed, for example exterior grade gypsum board and "Dens-Glas Gold," did not exist at the time the simulations were performed. Several assumptions were used to characterize the performance of the nonstucco-clad systems. One of the more important assumptions was to choose the same water-penetration characteristic as for the stucco walls. For example, the water penetration was assumed to be similar for a "real" galvanized metal-clad system as for the vinyl, T111, and Hardiplank. While this may not always be the case, it allows the comparison on how incidental water management occurs in each of the walls with similar penetration loads.

In Fig. C29, nonstucco cases 1 through 3 using vinyl siding are compared. The total wall moisture content is shown in these figures. The vinyl was assumed to be porous, and local mixing (along the height) was allowed with the outside air. As these systems allowed localized ventilation, the results show a net drying behavior when compared to the stucco-clad walls over the 2-year simulation period. In these three cases, no moisture storage capability was present for the vinyl cladding. As such, the walls were capable of handling the incidental water that penetrated into the wall. The case 3 wall displayed the highest drying potential with the foam sheathing.

In Fig. C30, the moisture content results are shown for the OSB sheathing for case 1, plywood sheathing for case 2, and GSB for case 3. Results are similar to the total moisture for the sheathing boards.

In Fig. C31, the plywood moisture content is plotted for cases 2 and 4. Case 4 employs galvanized metal with a 12.5-mm air gap, while case 1 has vinyl with no intentional air gap. The metal cladding seems to result in a lower moisture content on the plywood than the vinyl for case 2. Figure C32 compares cases 4 and 5, plywood and OSB, as a sheathing board with galvanized metal cladding. Results show that while case 4 with the plywood sheathing has a slightly better drying performance, but it also has a higher wetting capacity.

Figure C33 shows results of the use of Hardiplank as the exterior cladding with either 4-mil poly or kraft-paper facing on the 2×6 insulation. Negligible differences were observed. It is important to note that material property data on this board were not readily available and were approximated.

In Fig. C34, T-111 cases 10 and 11 show GSB sheathing moisture contents. Approximations were also made for this material. Results show negligible differences on application methods for interior vapor control strategies.

Summary

In the nonstucco claddings, the capability of the cladding systems to store water is limited in comparison to the stucco-clad cases. In most of these nonstucco-clad walls, a ventilation drying capability was present in the wall system. This, in addition to limited moisture storage capability in the exterior cladding, reduced the available moisture in the rest of the wall. As a result, less water was stored in critical elements of the wall.

5.5 WALL RANKING

The wall performances that were shown and discussed in the previous sections were further analyzed in terms of the risk to mold growth. An approach developed by Viitanen (1996, 1997a, and 1997b) was adopted for this study. More details can be obtained in publications by Viitanen et al. (2000), Karagiozis and Salonvaara (1999a, 1999b, and 2001c), and Salonvaara and Karagiozis (1998). Essentially, time-dependent occurrences of wet and dry spells, wood species type, and temperature and relative humidity were used to determine mold-growth indexes. In Table 4, the relative ranking of all walls with initial relative humidity of 85% and water penetration of 2% is displayed. The ranking was performed for each class of simulations. A ranking of one from one class of simulation does not correspond to the same level for a ranking of one in another class. A larger number in the rankings indicates a higher water management capability of the walls. This ranking encompasses the effects of wall system behavior under the same climatic conditions of Seattle. All basic wall systems investigated in this study were analyzed. A number was assigned by ranking the walls in terms of the risk of mold growth in the wall. It is believed that this is the first study that employs the use of a mold-growth index to assess the relative performance of a variety of wall systems.

Table 4. Relative ranking of walls in terms of risk to mold growth

Wall rankings (relative ranking for example 1: less risk …15 higher risk)					
Post 84 stucco walls		Pre-84 stucco and cedar walls		Post 84 nonstucco walls	
Wall case	*Ranking #*	Wall case	*Ranking #*	Wall case	*Ranking #*
3A	*4*	2	2	1	*5*
3B	*2*	5	3	2	*6*
4A	*8*	6	1	3	*8*
4B	*7*			4	*7*
6A	*11*			5	*7*
6B	*5*				
6C	*6*				
8	*6*			8	*2*
9	*9*			9	*1*
14A	*3*			10	*3*
14B	*1*			11	*4*
15A	*10*			12	*9*
15B	*12*			13	*10*
16A	*13*				
17A	*14*				
19A	*15*				

6. CONCLUSIONS

The moisture performance of three different classes of wall systems has been investigated in the context of the preliminary hygrothermal analysis of walls in Seattle. The results reported in this phase specifically address the moisture performance of walls designed with loads that have some unintentional water penetration. The results have been developed in a manner to present the relative performance of the walls in the same climate with similar water penetration effects. The analysis was performed with the best available input data. Several limitations should be recognized within the context of this study.

Results showed that selection of wooden sheathing boards on interior vapor-tight assemblies does not significantly influence the performance of stucco-clad walls. A larger effect was observed when the interior vapor control is made vapor open. When continuous cavity ventilation is employed, the effect of the selection of the type of sheathing board on the hygrothermal performance of the wall was found to be negligible.

When comparing oriented strand board sheathing performance against the performance of exterior grade gypsum, the differences are very significant in terms of the amount of moisture content present in the walls. Moisture content alone does not indicate their respective durability as durability is directly related to the combination of relative humidity and temperature, mechanical, chemical, and biological properties of the substrates. This study did not investigate the durability performance of either sheathing.

In terms of interior vapor control, inhabitant behavior must be considered during the wall hygrothermal design stage. If interior relative humidity is maintained below 60%, then a latex primer and paint may perform better than the use of PVA or even a polyethylene sheet. When the interior environment is maintained at a higher relative humidity, then stricter vapor control is needed.

Multilayered building paper was experimentally shown to enhance the drainage capability of the stucco walls in a set of preliminary drainage tests. Water entry was found to be present in either dual- or single-layered systems, but single layers allowed substantially more water penetration.

The effectiveness of the building paper was found to depend on the type of vapor control strategy used on the interior. This connectivity is important to recognize. Results have shown that two layers of a 60-min paper system performed better than a single layer of No.15 felt paper. In general, weather-resistive building papers play a very important role in a stucco-clad wall system. Vapor diffusion control is only one element of control these membranes offer.

Continuous venting of stucco walls provides a beneficial drying performance, which is not present in walls that are not vented. Continuous ventilating of stucco walls provides a further improvement in the drying performance of the stucco walls as compared to vented walls. The effectiveness of the weather-resistive barrier vapor diffusion control was found to be significantly smaller in the presence of ventilation, thus the choice of the weather-resistive membrane should be made for reasons other than vapor control.

Increasing the insulation levels from 89 mm to 140 mm or even 280 mm resulted in slightly higher moisture accumulation. Walls that have been designed with a more vapor-open interior showed negligible effects on moisture content accumulation caused by increased amounts of insulation applied to the walls. The limiting factor was establishing an acceptable interior environment, limiting the interior to 60% relative humidity.

The indoor environment plays a critical role for the performance of all wall systems. Increasing interior ventilation rates decreases the interior vapor pressure and relative humidity and enhances the performance of the stucco wall during different times of the year. The amount of ventilation required to reduce the interior relative humidity may be prohibitively large, and other means of dilution by dehumidification may be beneficial when high interior moisture loads are present.

Operation of the mechanical system caused increased moisture accumulation of the stucco-clad wall system. The current Seattle code requirements may have contributed to increased moisture contents in the stucco wall systems, but it appears that mechanical ventilation per code merely acts to augment the existing significant air pressure differences caused by wind and stack effect.

Water penetration is the most critical influence on moisture management of wall systems. Neither vapor diffusion nor air leakage is comparable in magnitude. Water penetration may be several orders of magnitude greater than allowed by simple vapor or even liquid diffusion because of wind-driven rain. Water penetration at even a small fraction of the total rain load (1 to 2%) must be included in designs to represent realistic boundary conditions. The presence of windows and joints amplifies the local hygrothermal influences, as water loads become many times greater that in walls without windows and joints.

Exterior gypsum provides an additional resistance to both thermal and moisture flow that was found beneficial for a 2×4 old stucco wall arrangement. In this wall arrangement, concepts of “flow-through moisture control” seem to have very positive hygrothermal performances. At different times of the year, the conventional stucco wall displays higher amounts of moisture accumulation, while at the same time, allows more rapid drying. Cedar siding was found to permit a synchronized moisture performance with distinct moisture drying and wetting distributed during the year.

In all of the nonstucco claddings, the capability of the cladding systems to store water is limited in comparison to the stucco-clad cases. In most of these nonstucco-clad walls, a strong ventilation drying capability was present in the wall system. This ventilation factor reduced the available moisture in the wall components and limited moisture storage in the exterior cladding. This moisture performance resulted in walls that had less water stored in the critical elements of the wall.

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APPENDIX A

WALL LAYOUT

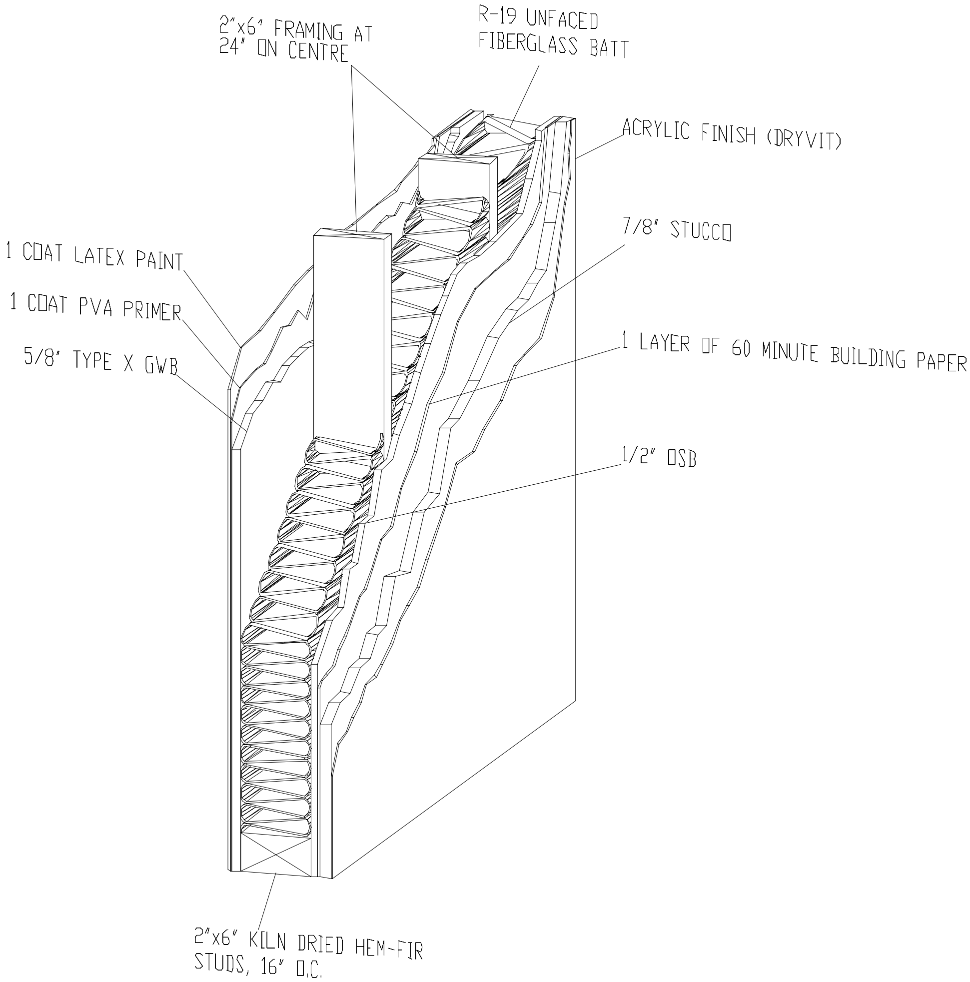
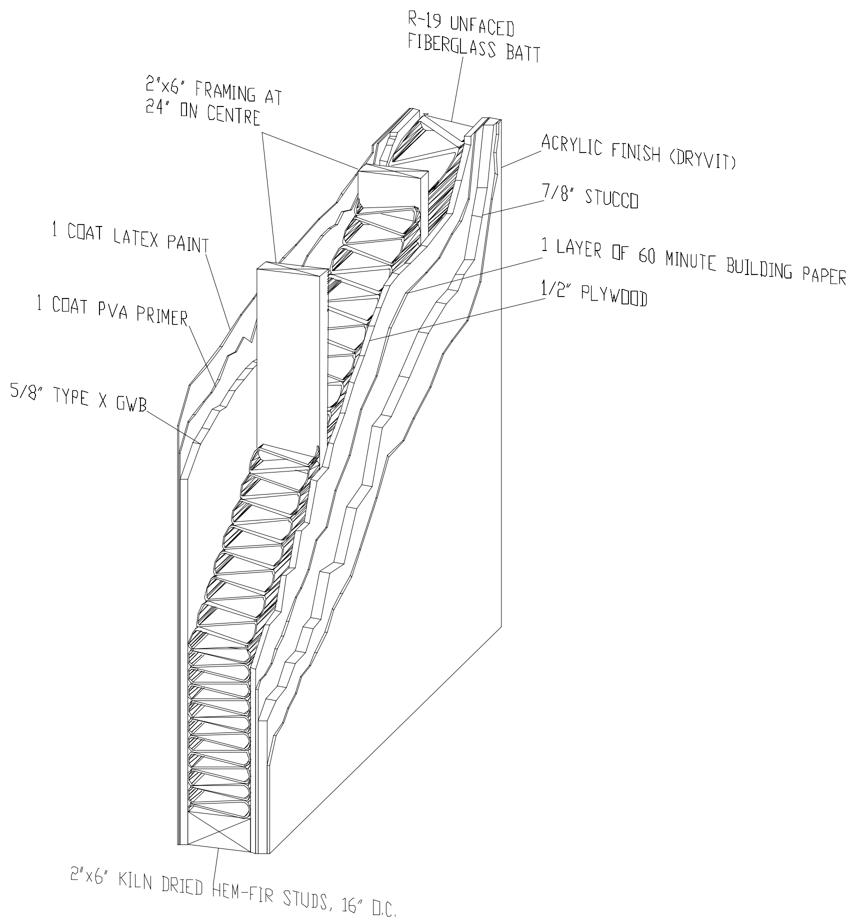


Fig. A1. Wall 3A.



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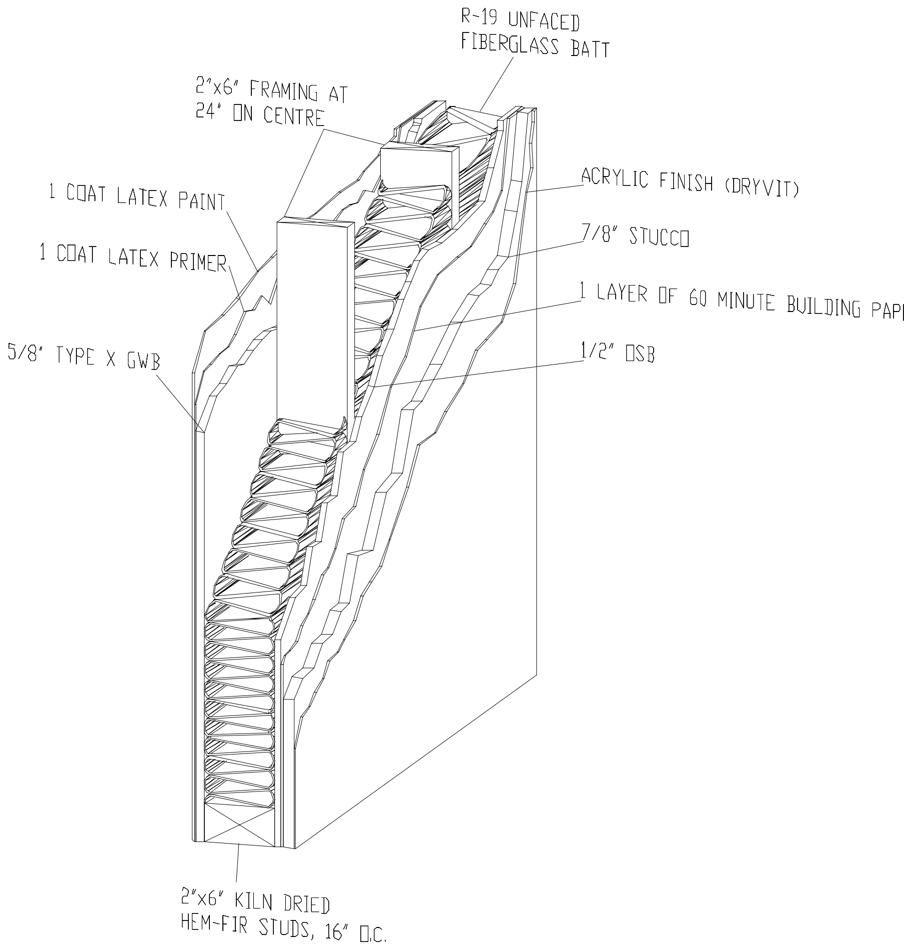

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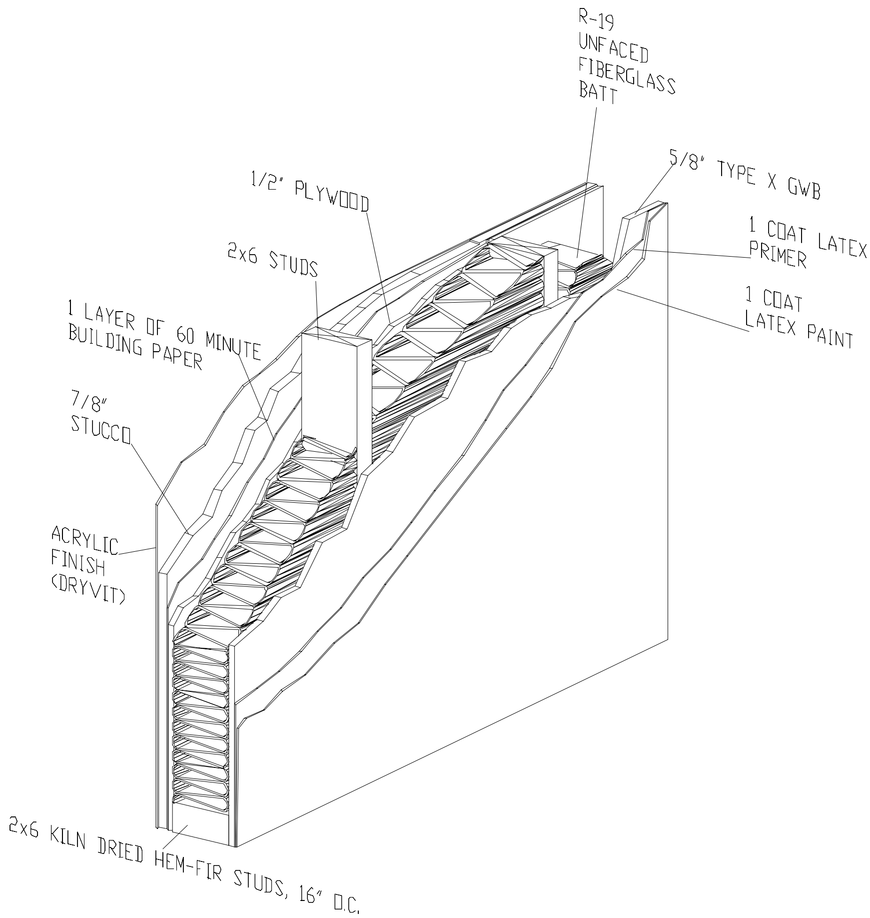

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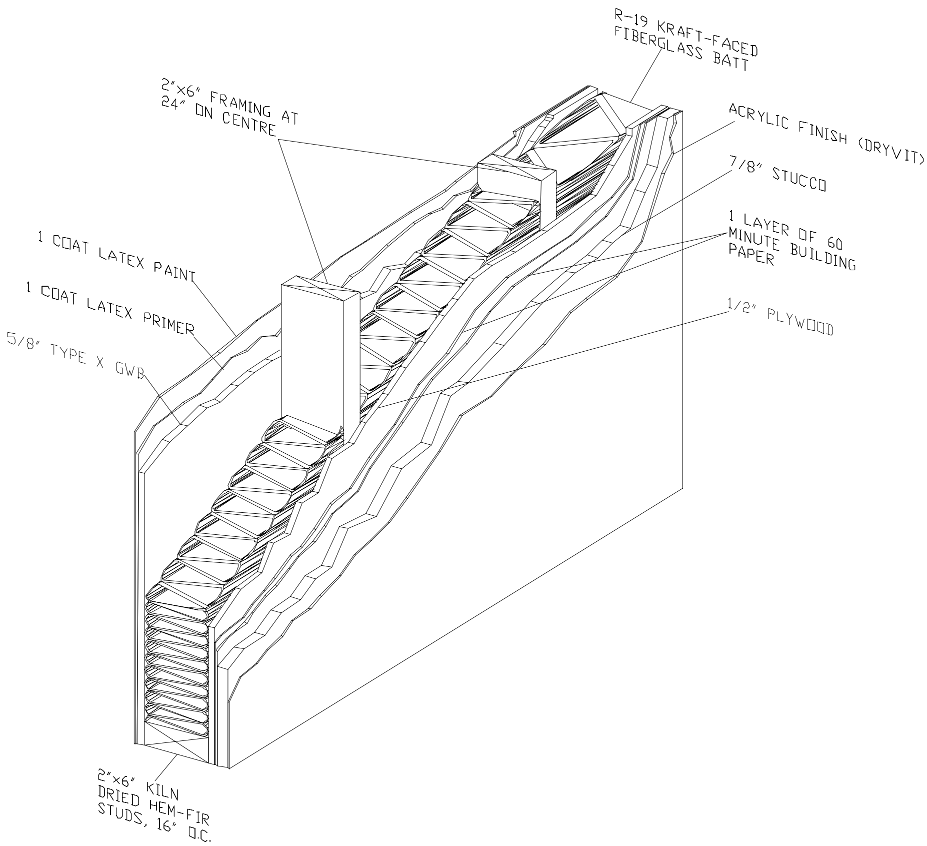

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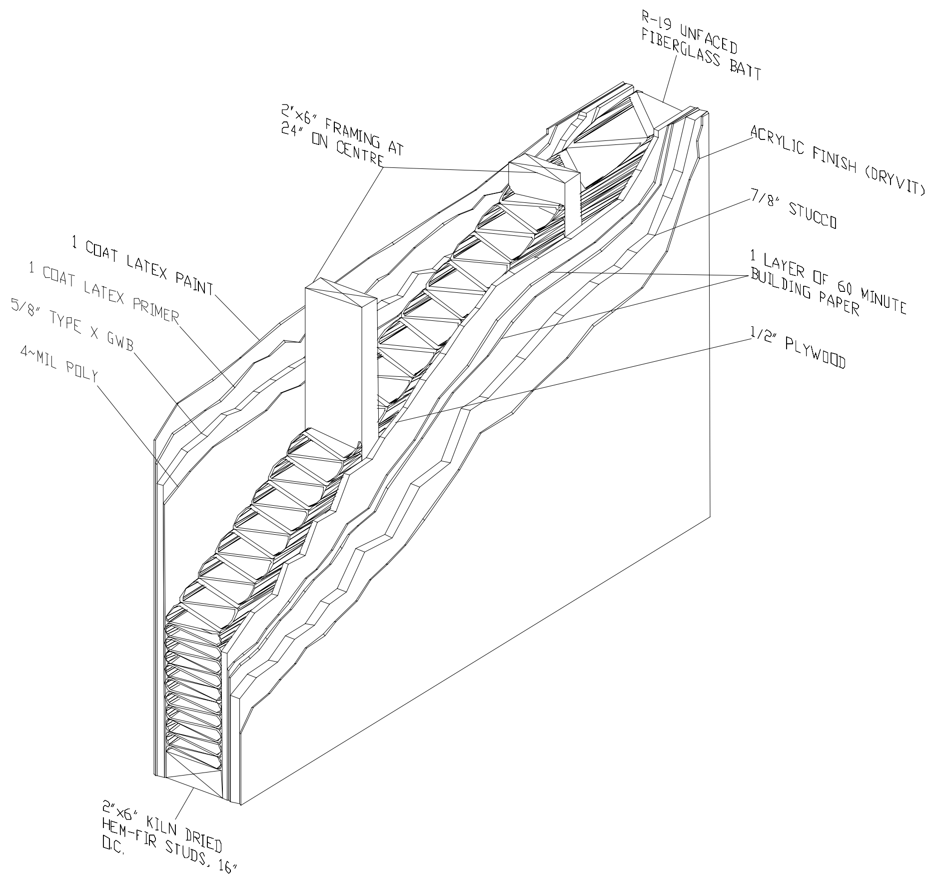

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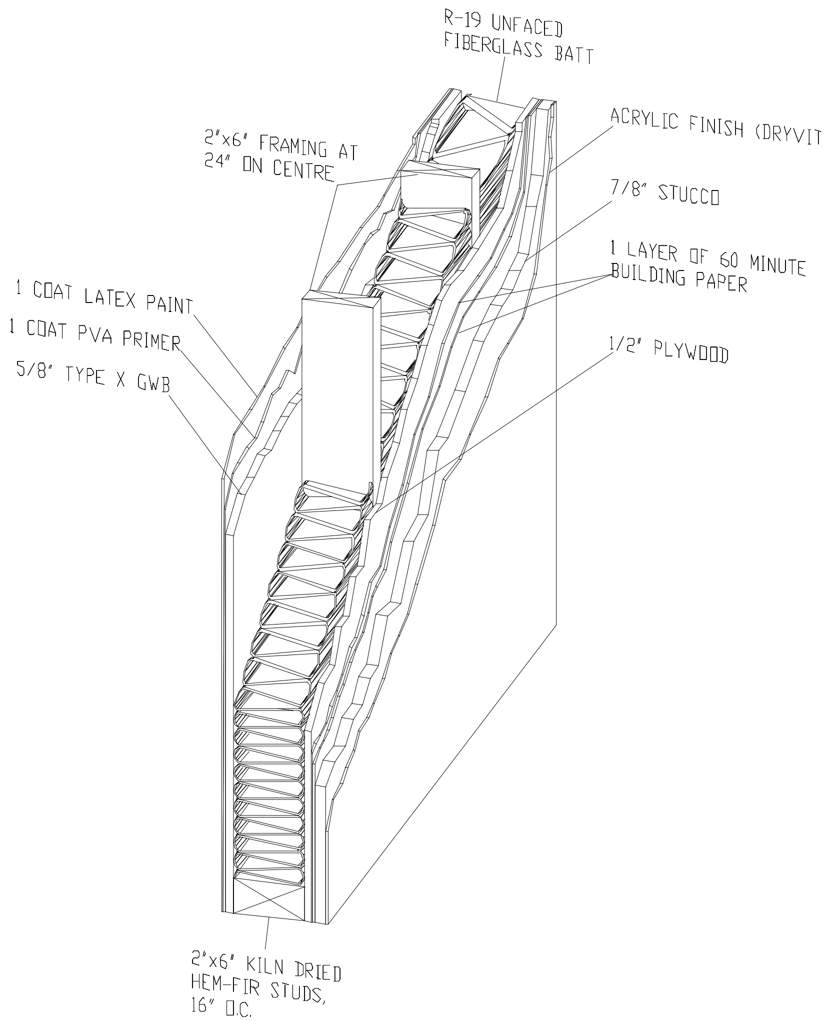

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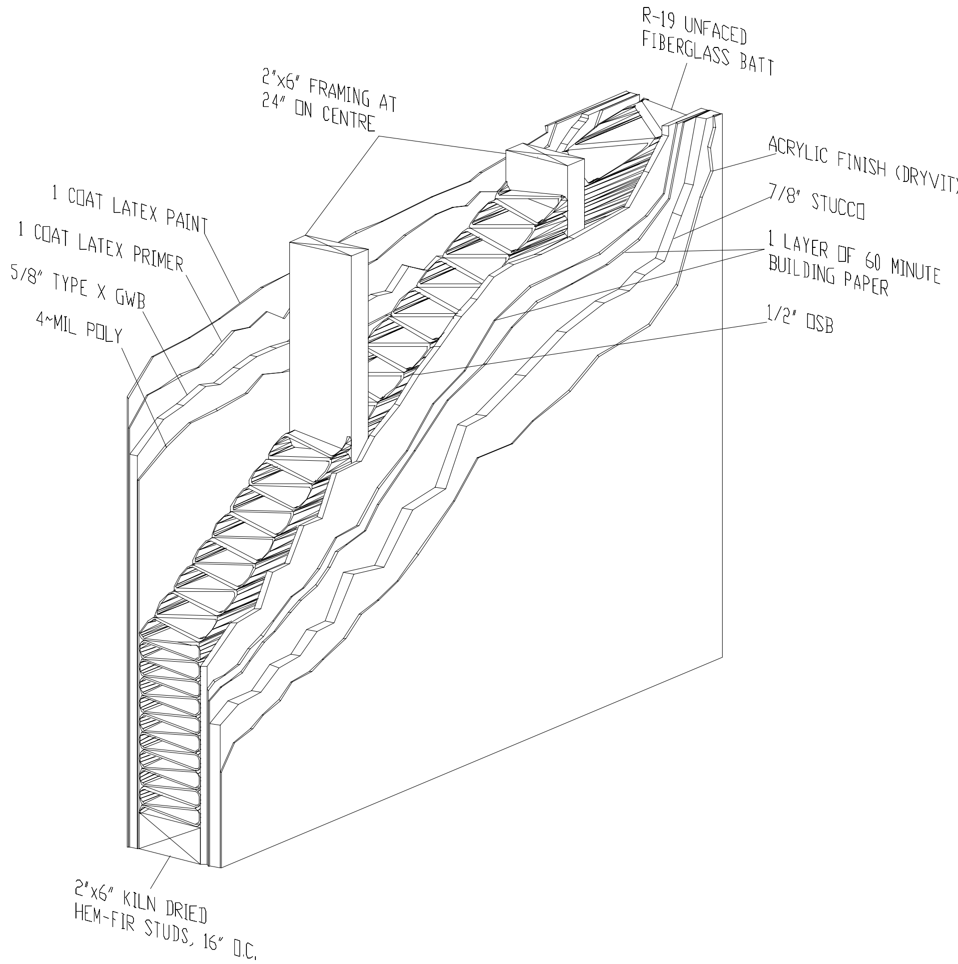

R-19 UNFACED
FIBERGLASS BATT
2"x6" FRAMING AT
24" ON CENTRE
ACRYLIC FINISH (DRYVIT)
1 COAT LATEX PAINT
7/8" STUCCO
1 COAT LATEX PRIMER
1 LAYER OF 60 MINUTE
BUILDING PAPER
5/8" TYPE X GWB
4-MIL POLY
1/2" OSB
2"x6" KILN DRIED
HEM-FIR STUDS, 16" O.C.

Fig. A8. Wall 8.

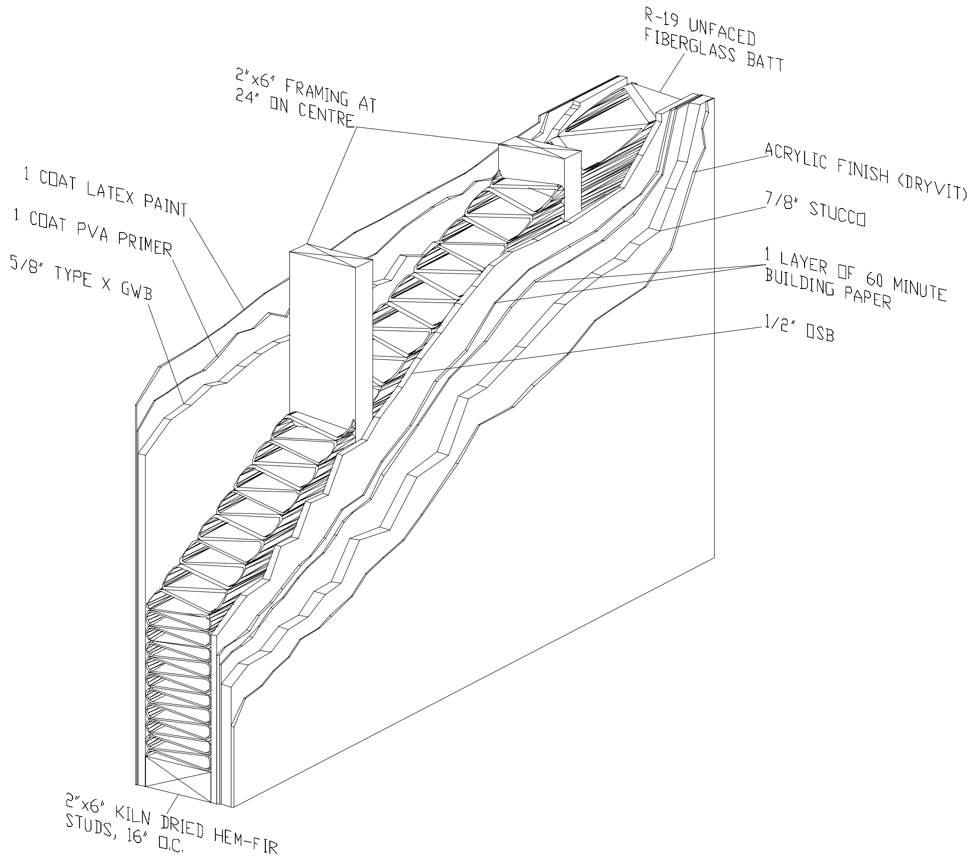
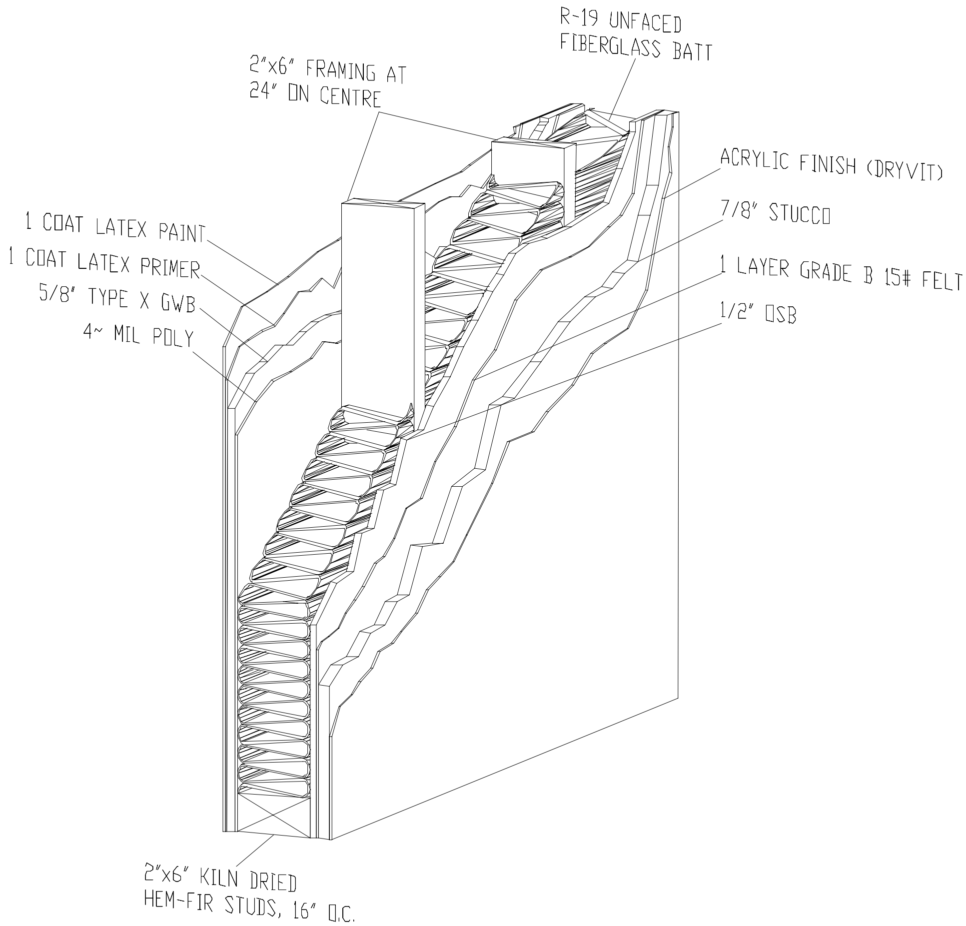

R-19 UNFACED
FIBERGLASS BATT
2"x6" FRAMING AT
24" ON CENTRE
1 COAT LATEX PAINT
1 COAT PVA PRIMER
5/8" TYPE X GWB
ACRYLIC FINISH (DRYVIT)
7/8" STUCCO
1 LAYER OF 60 MINUTE
BUILDING PAPER
1/2" OSB
2"x6" KILN DRIED HEM-FIR
STUDS, 16" O.C.

Fig. A9. Wall 9.



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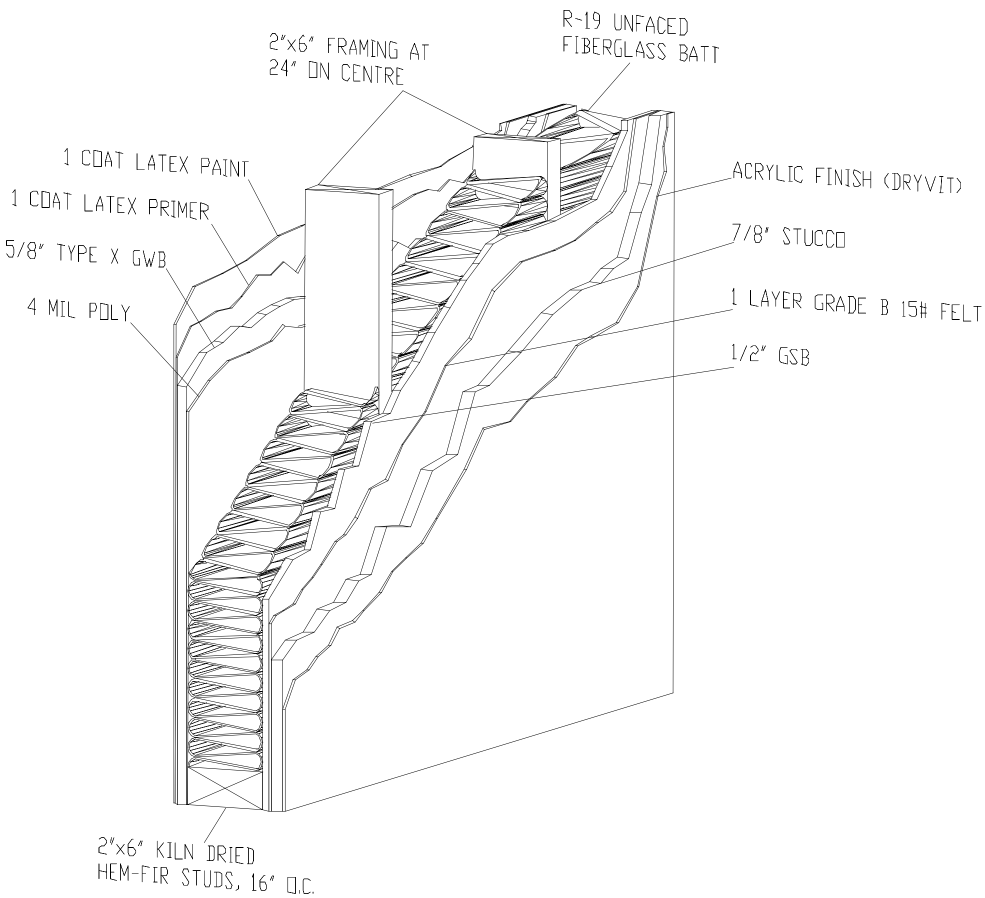

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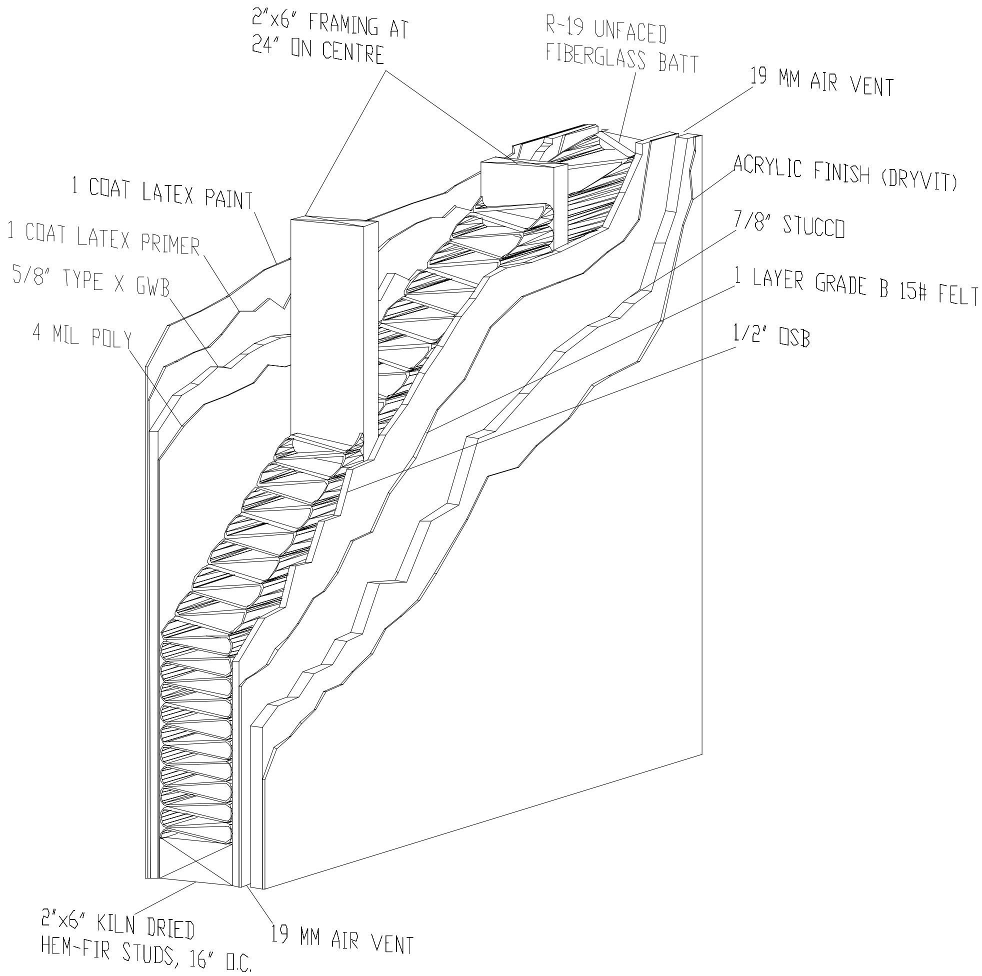

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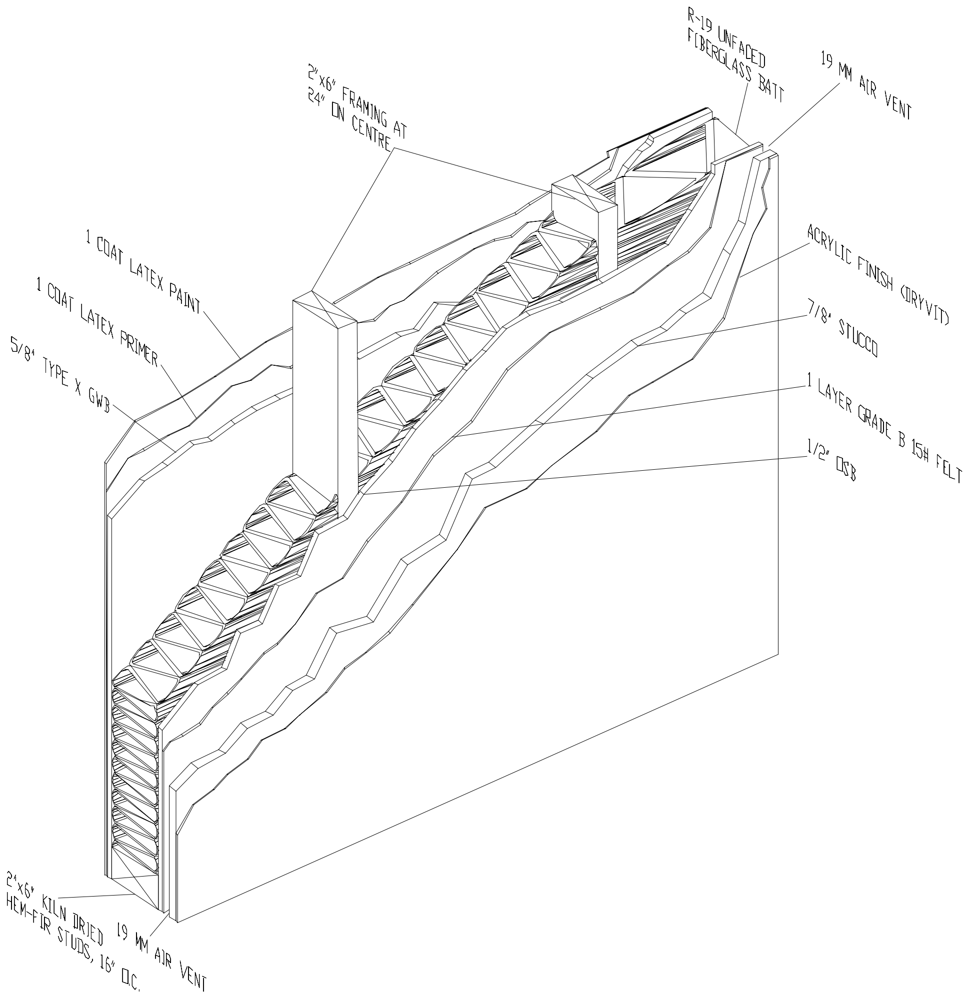

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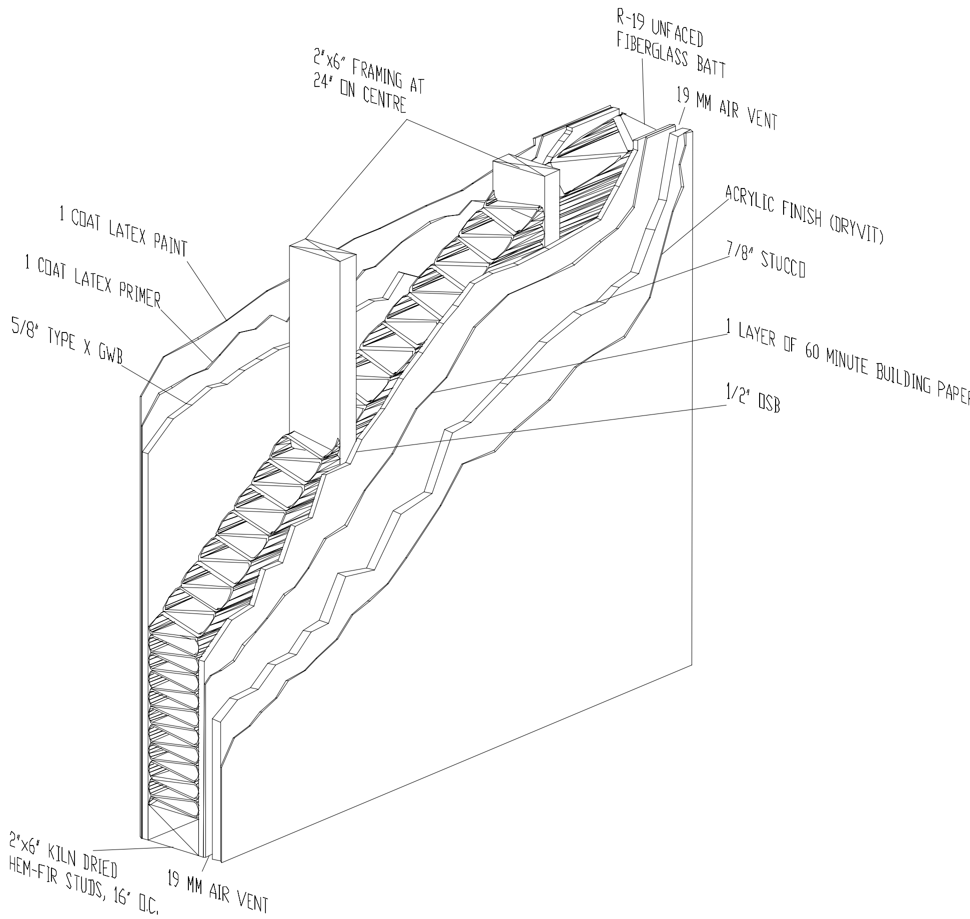

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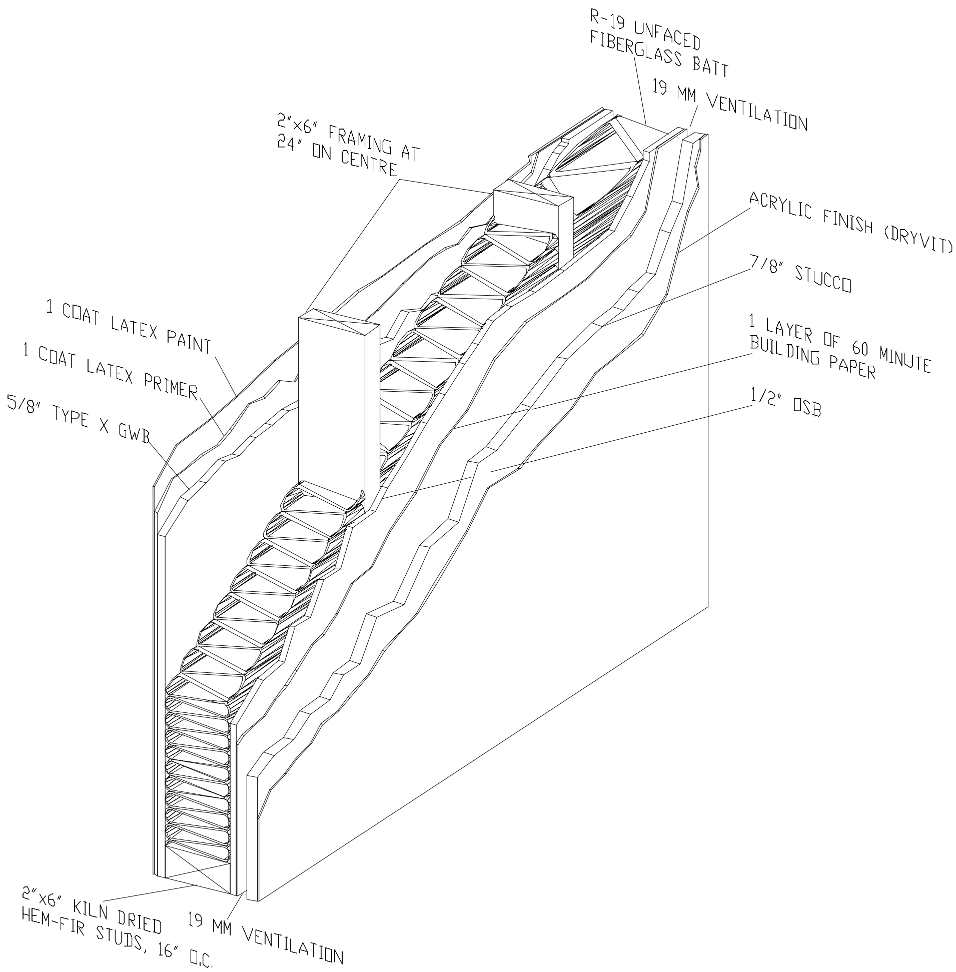

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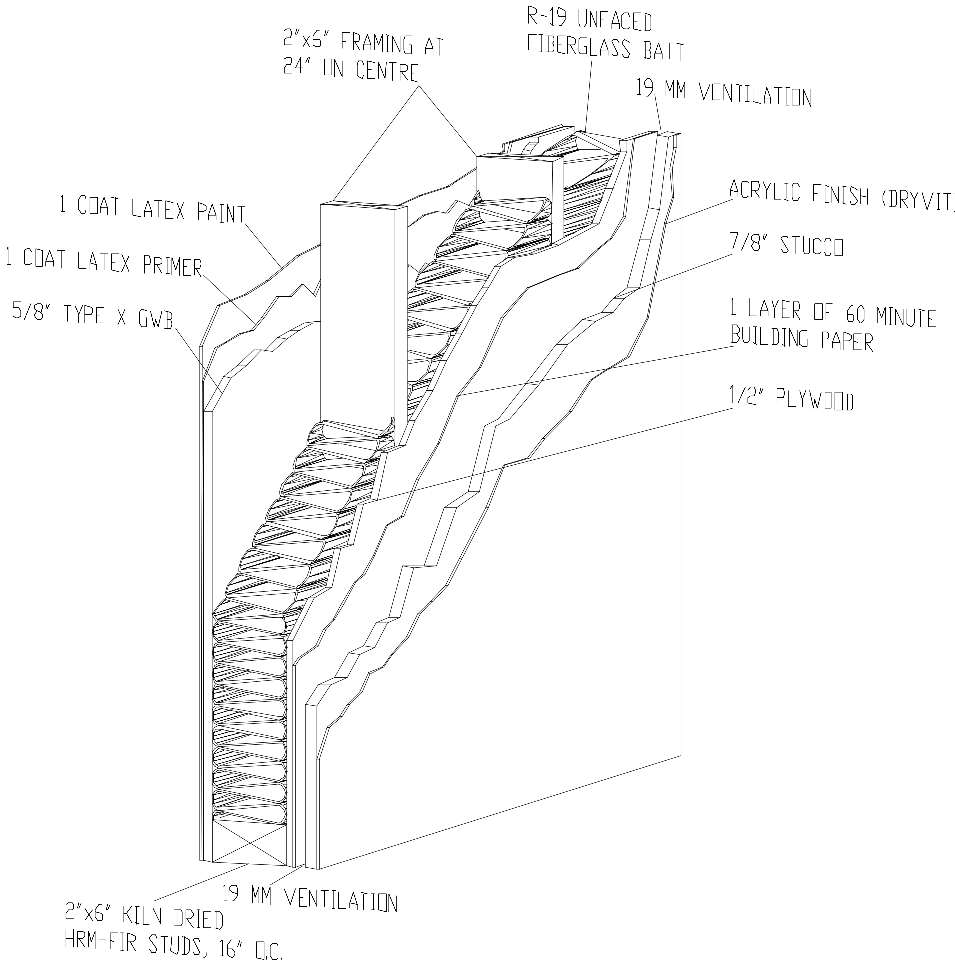


Fig. A16. Wall 19A.

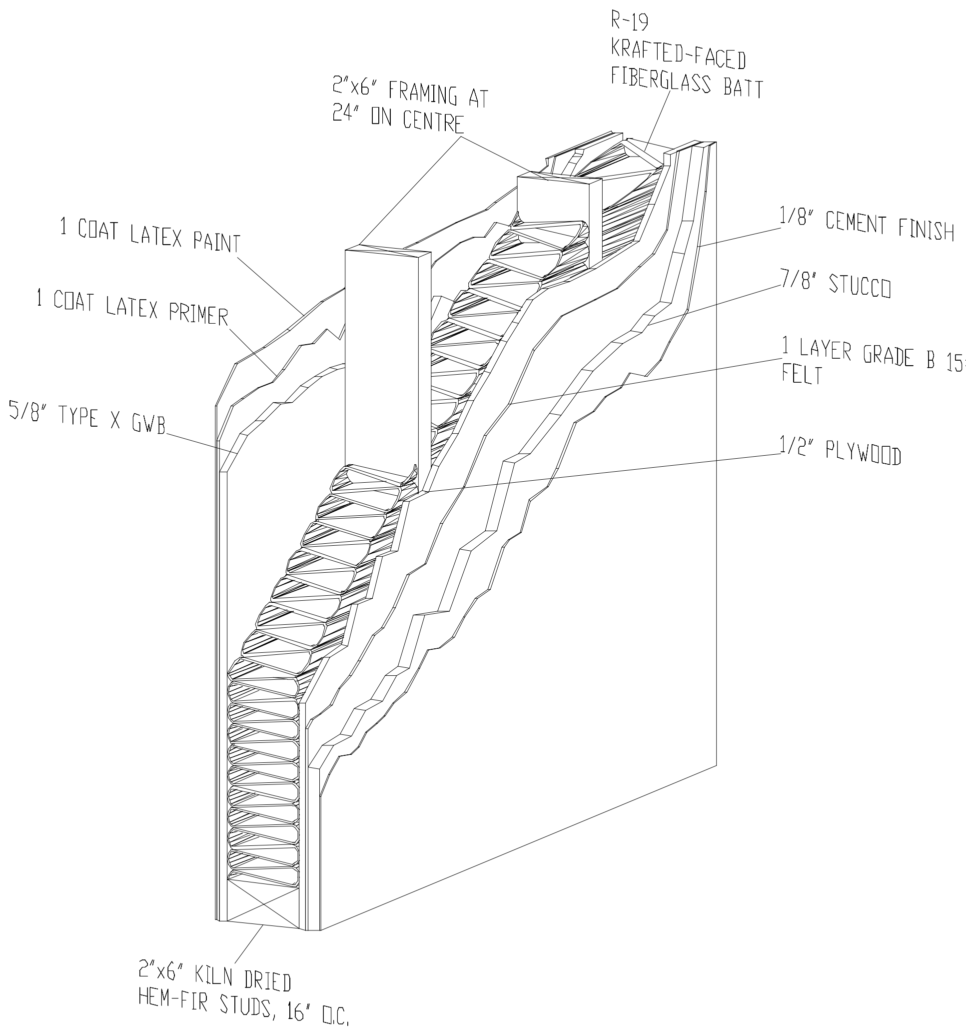


Fig. A17. Pre-1984 wall 2.

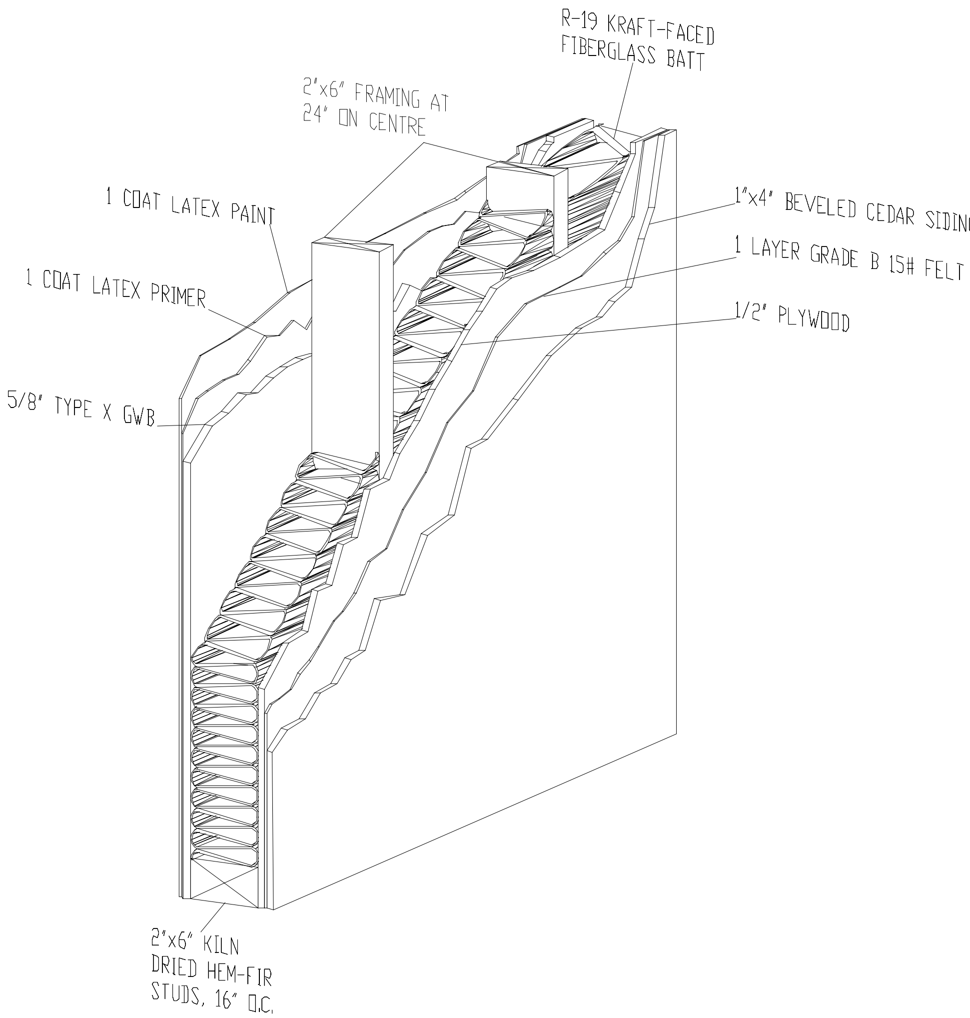


Fig. A18. Pre-1984 wall 5.

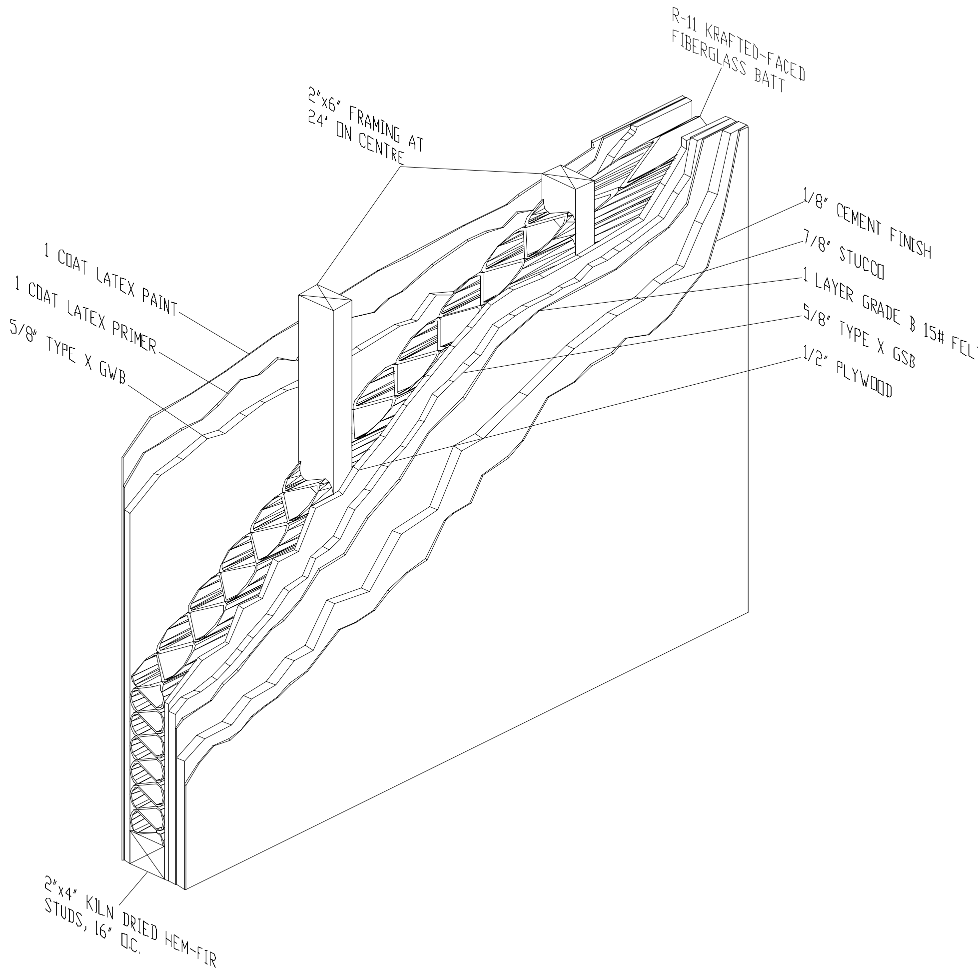


Fig. A19. Pre-1984 wall 6.

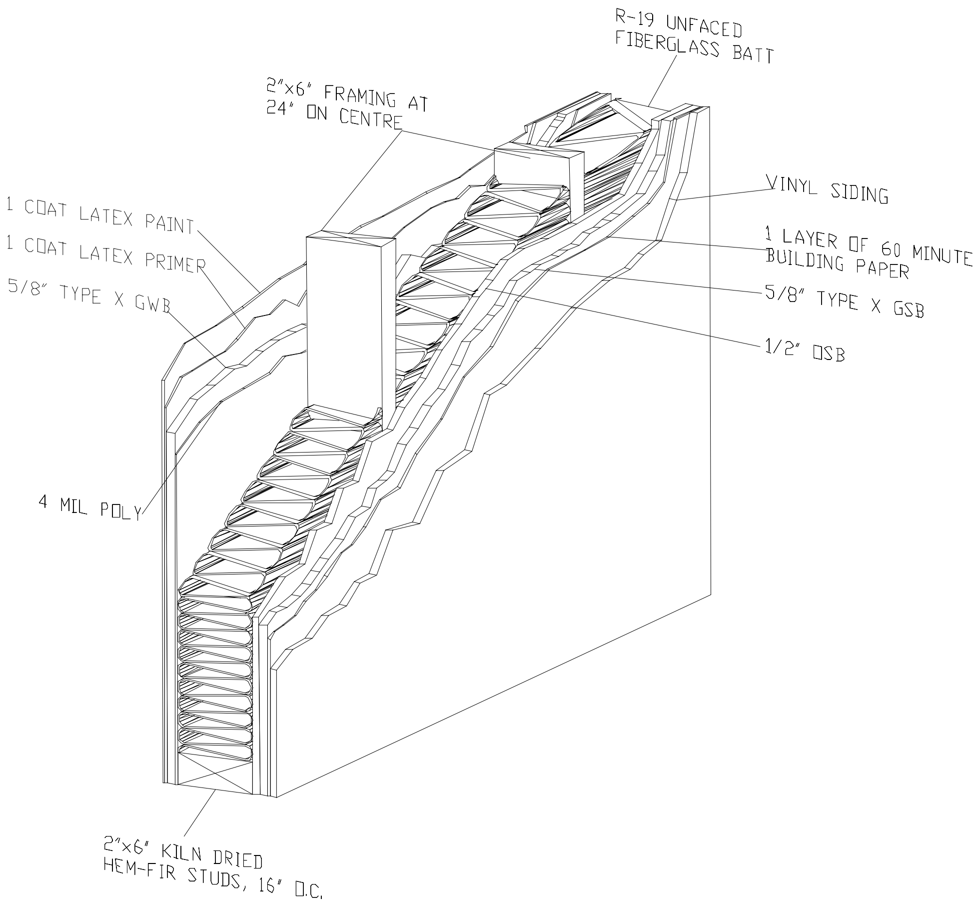
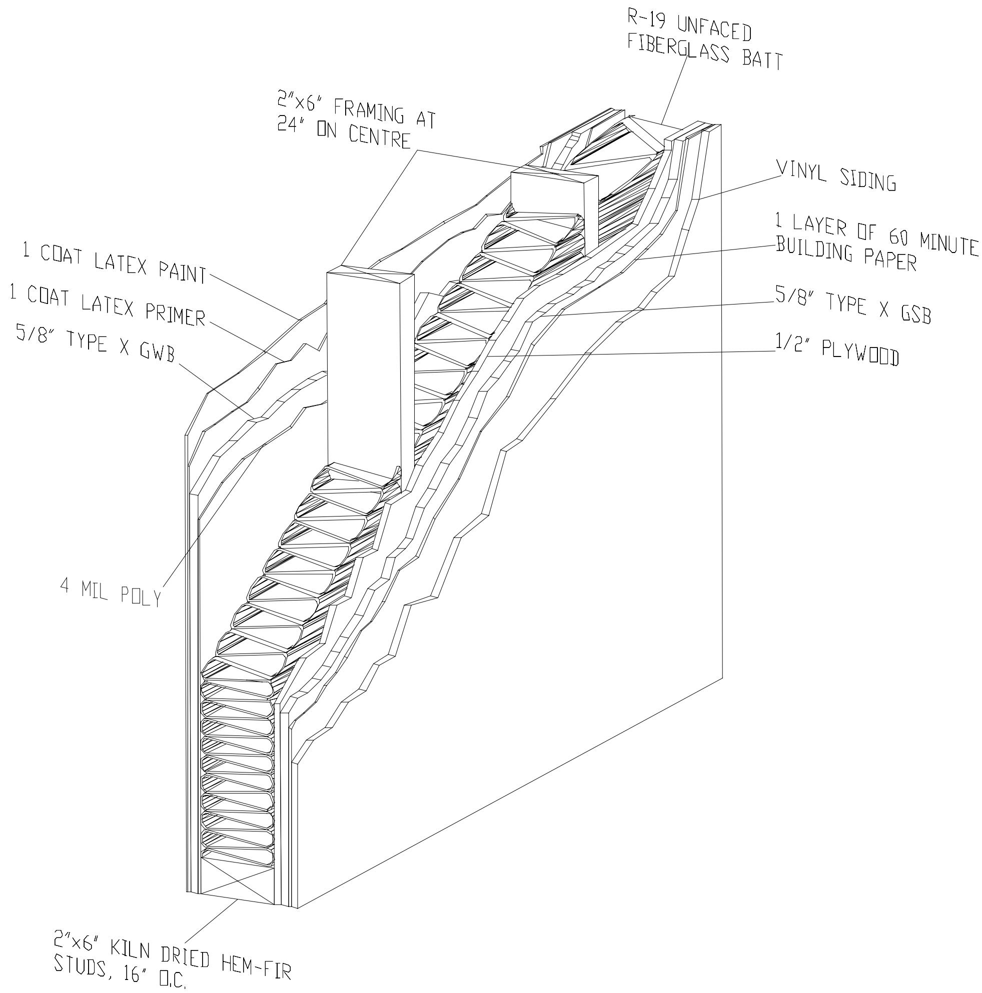


Fig. A20. Post-1984 nonstucco wall 1.



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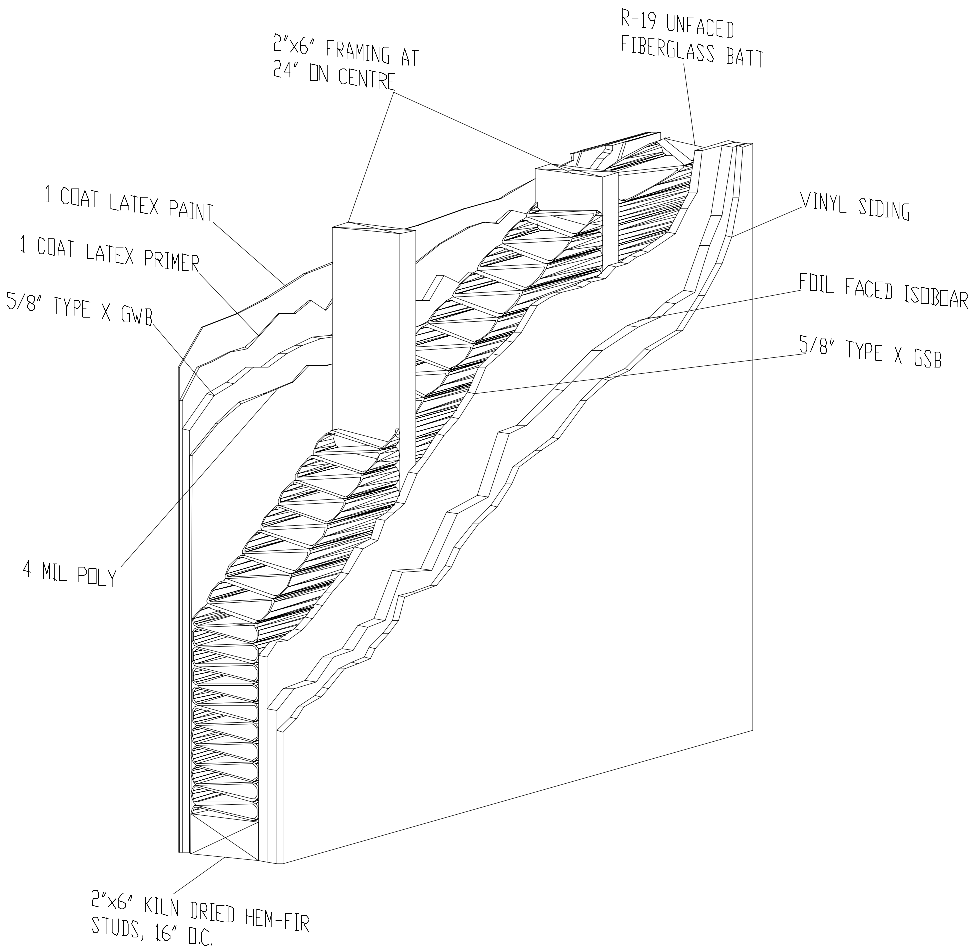


Fig. A22. Post-1984 nonstucco wall 3.

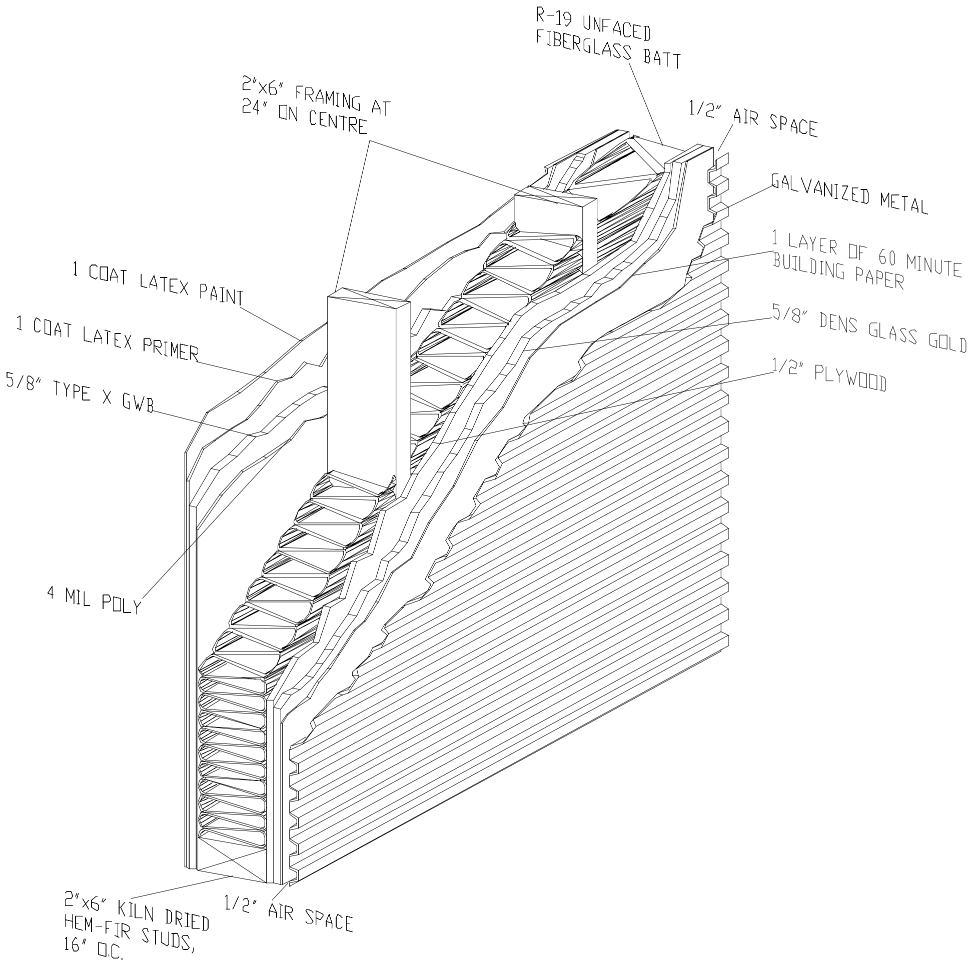
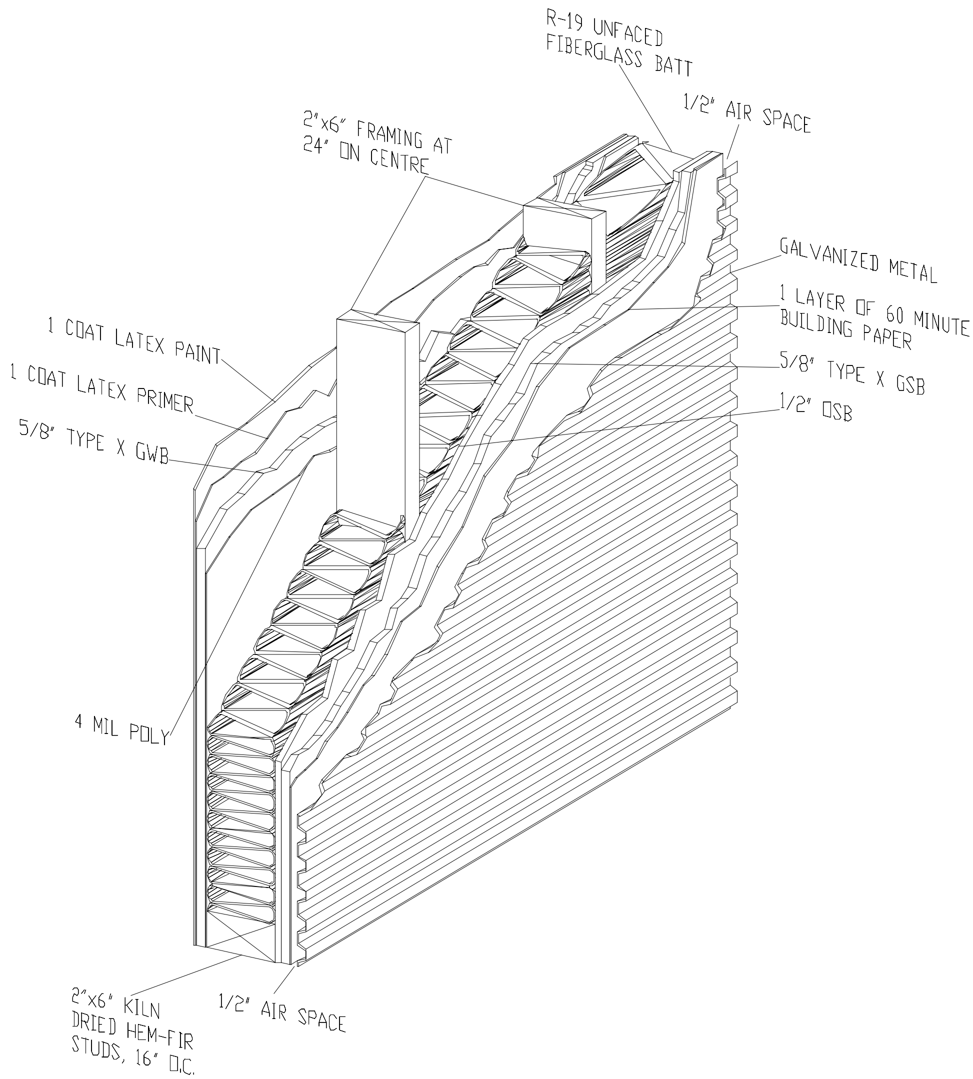


Fig. A23. Post-1984 nonstucco wall 4.



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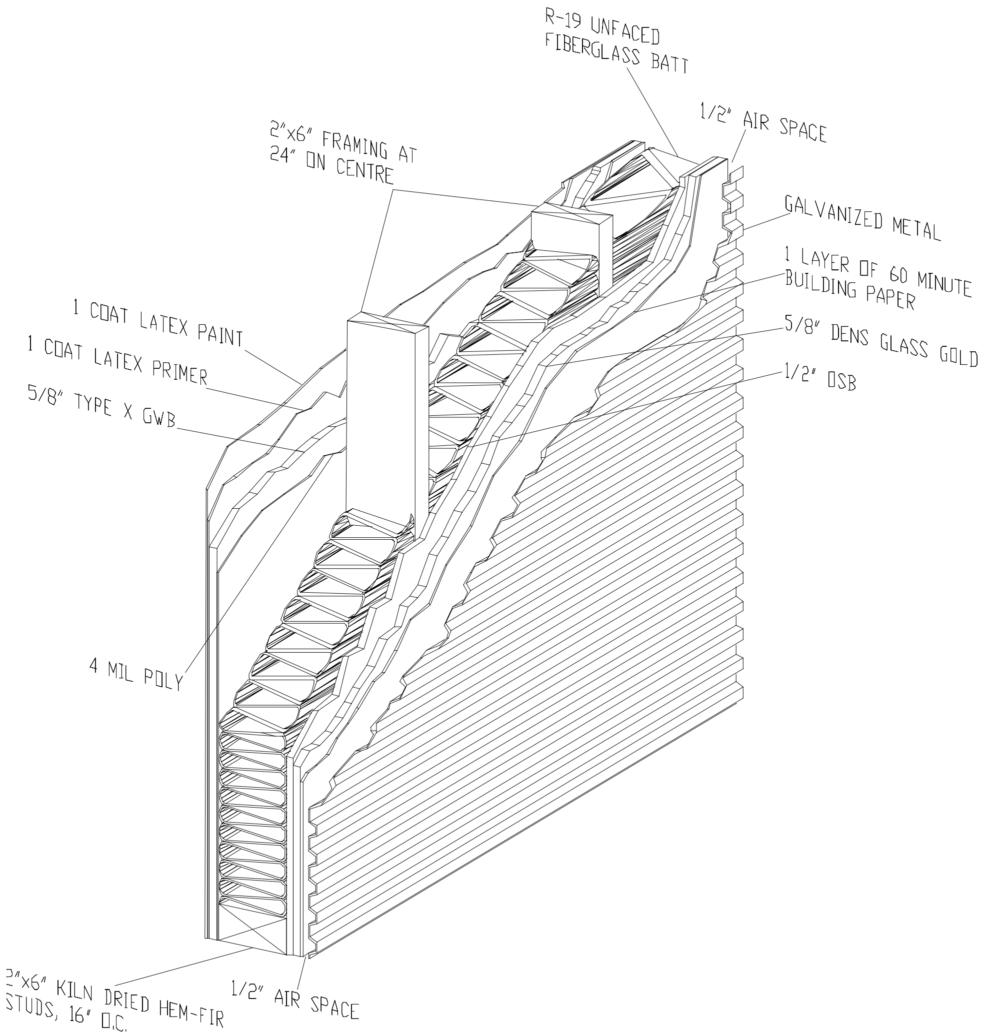


Fig. A25. Post-1984 nonstucco wall 6.

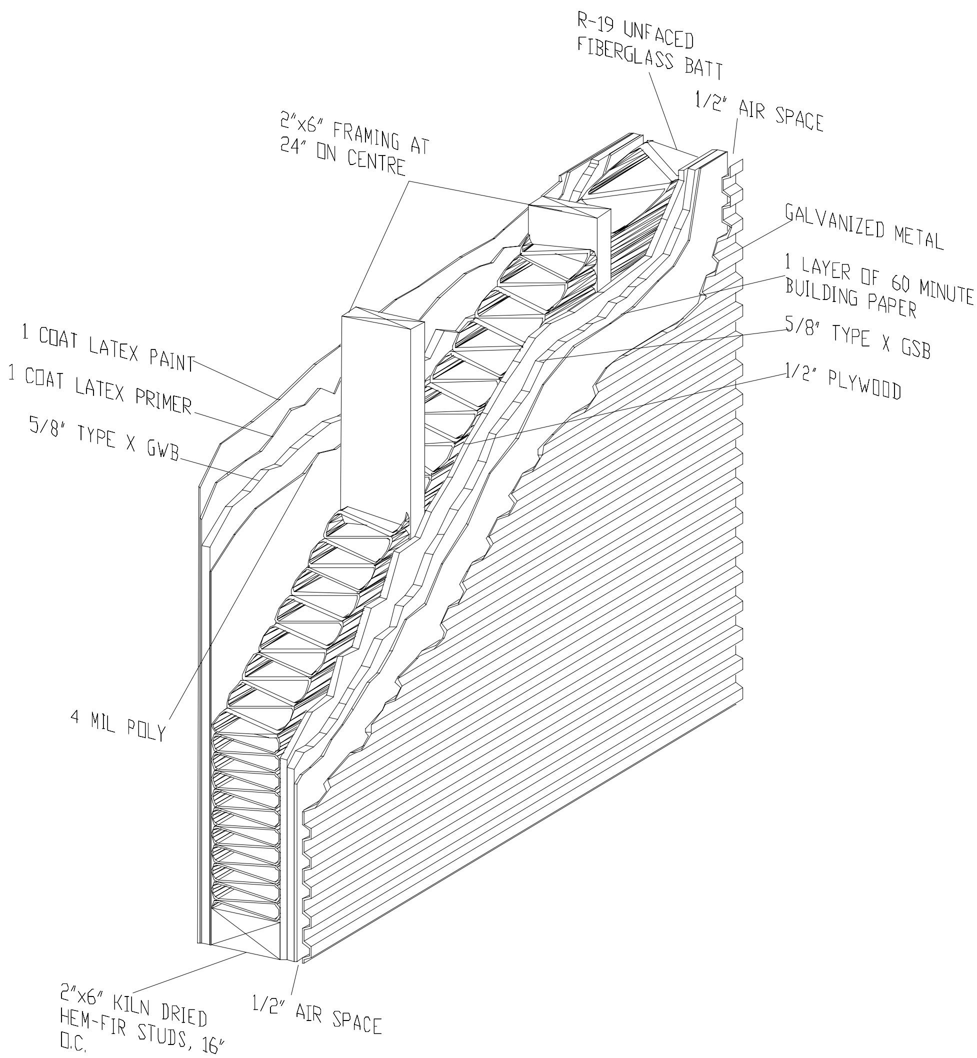


Fig. A26. Post-1984 nonstucco wall 7.

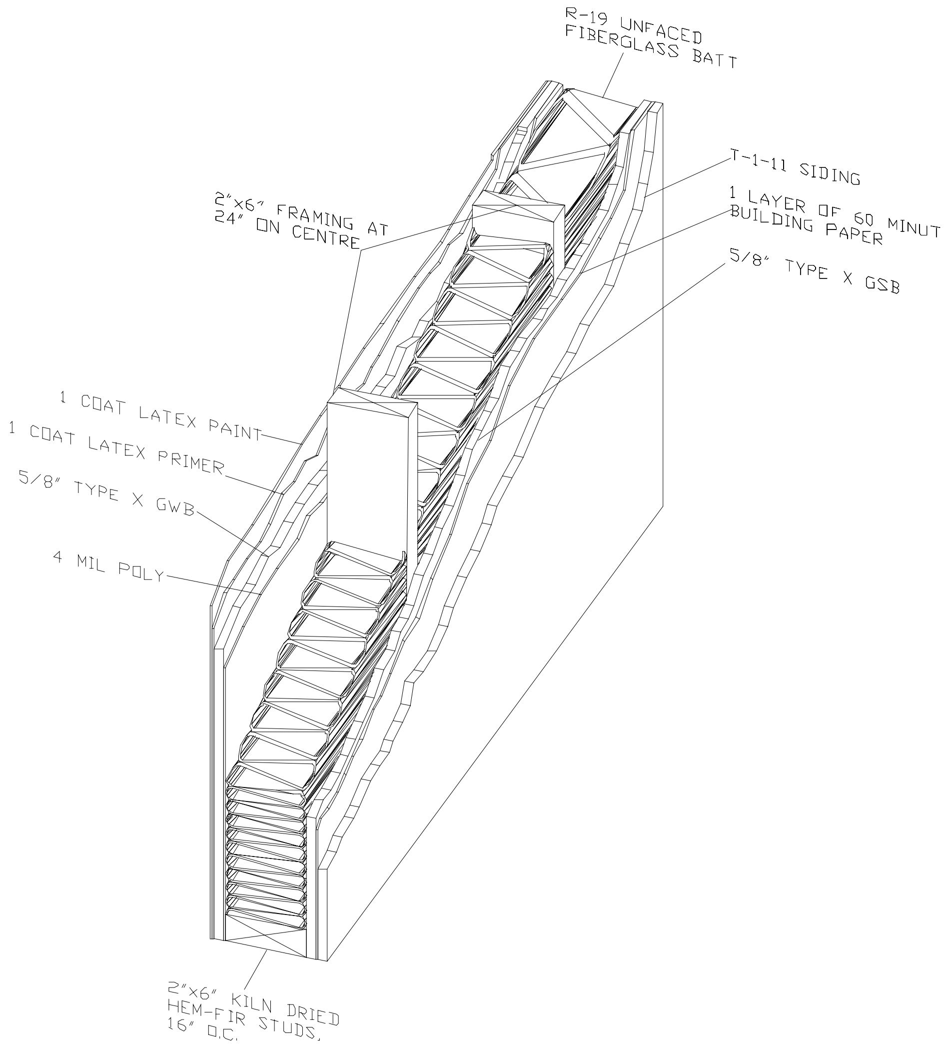


Fig. A27. Post-1984 nonstucco wall 8.

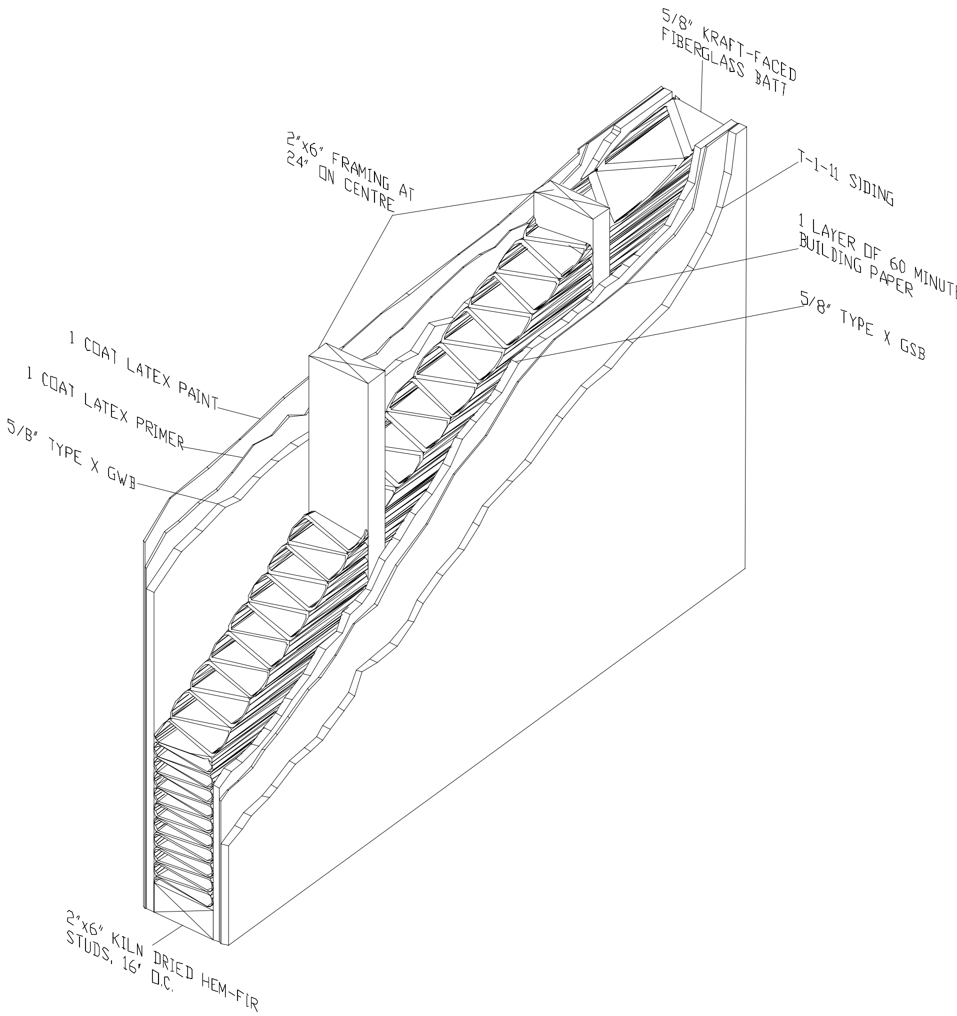


Fig. A28. Post-1984 nonstucco wall 9.

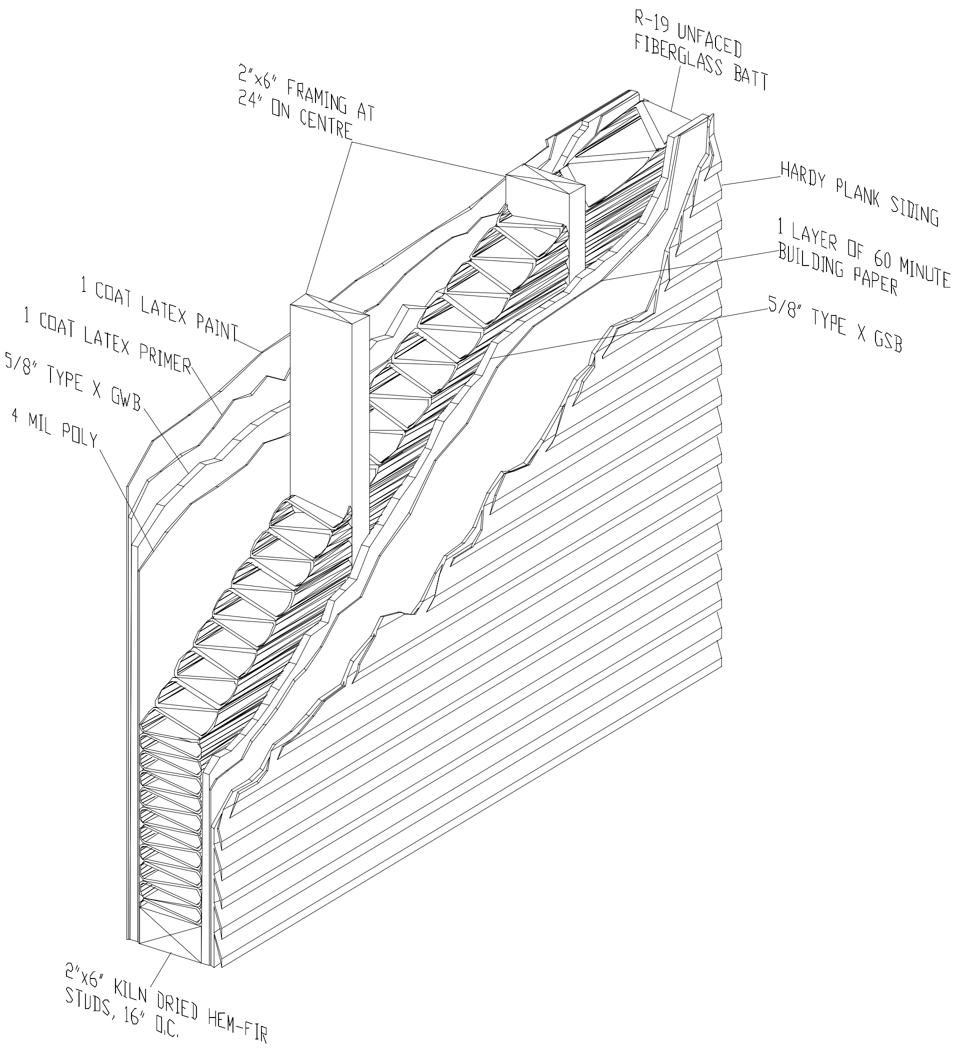


Fig. A29. Post-1984 nonstucco wall 10.

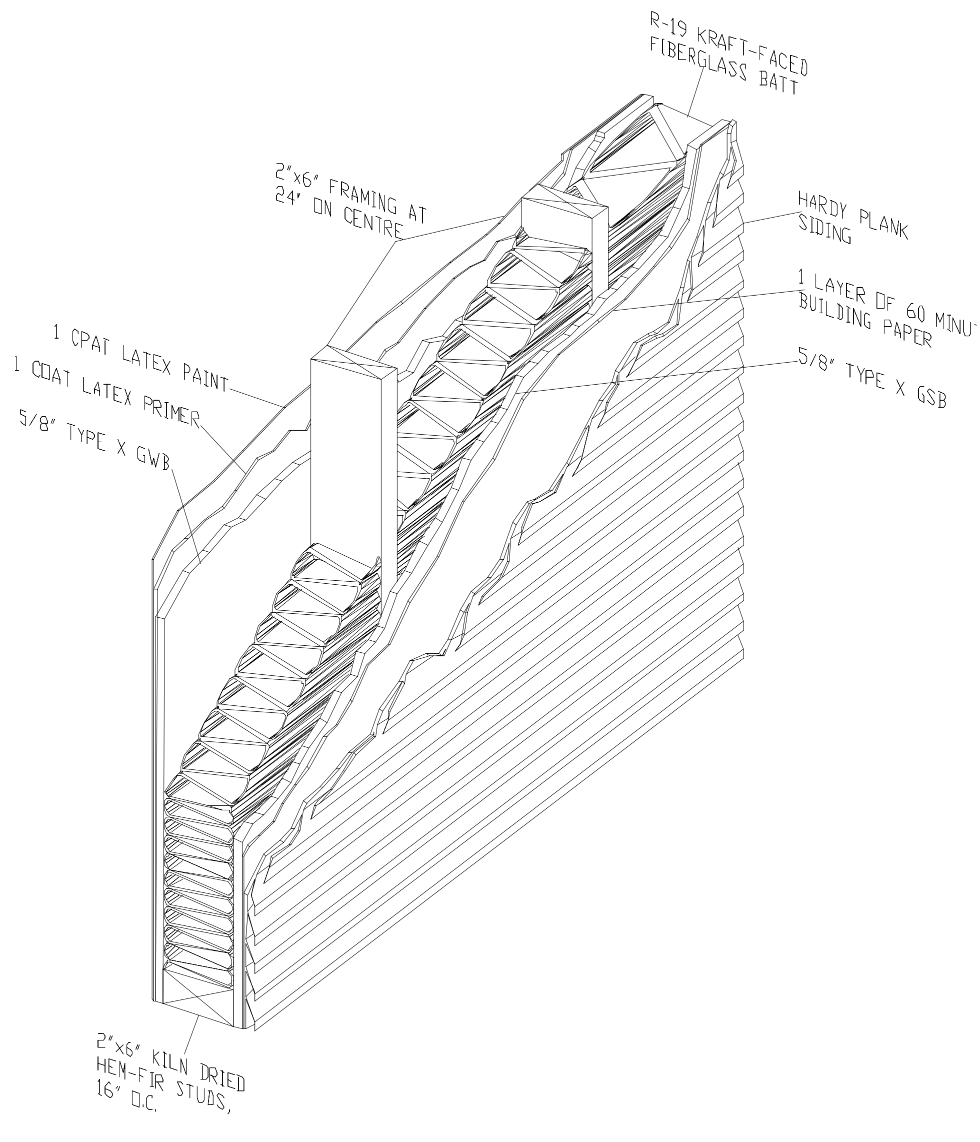


Fig. A30. Post-1984 nonstucco wall 11.

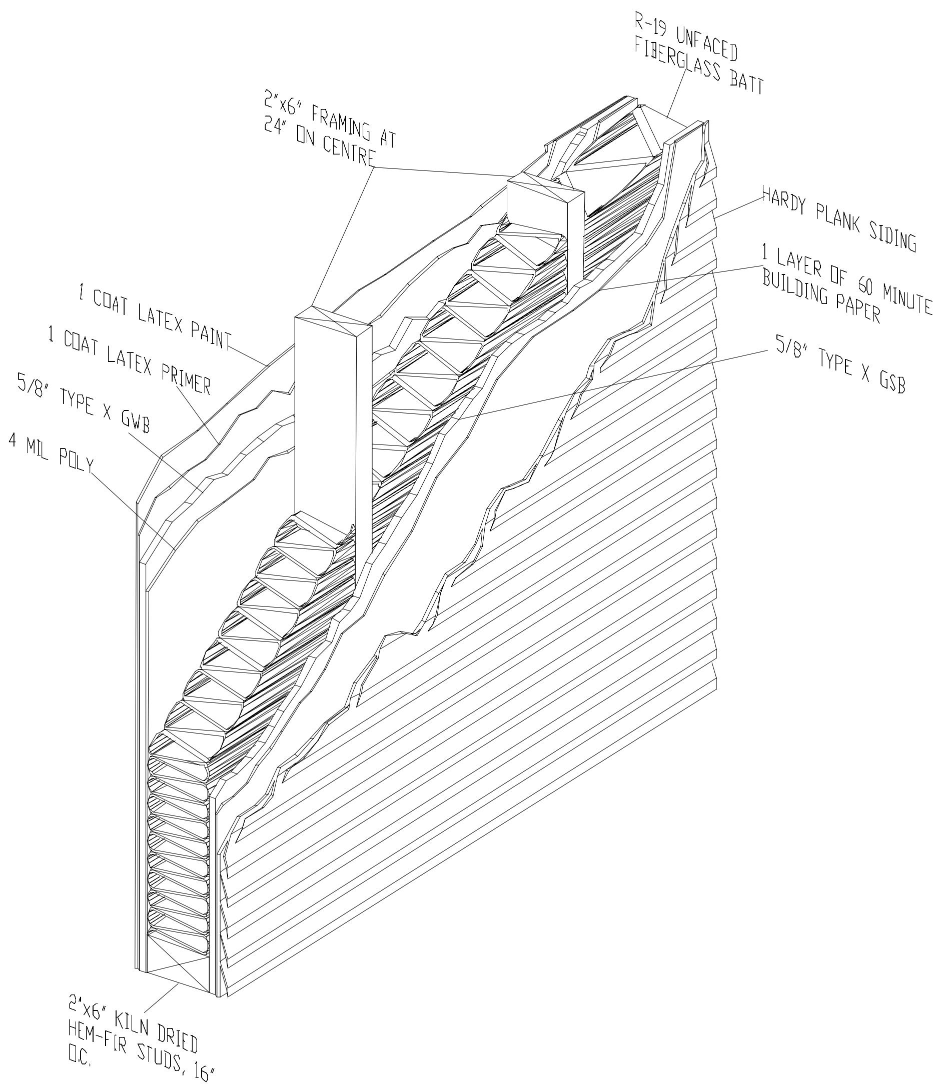


Fig. A31. Post-1984 nonstucco wall 12.

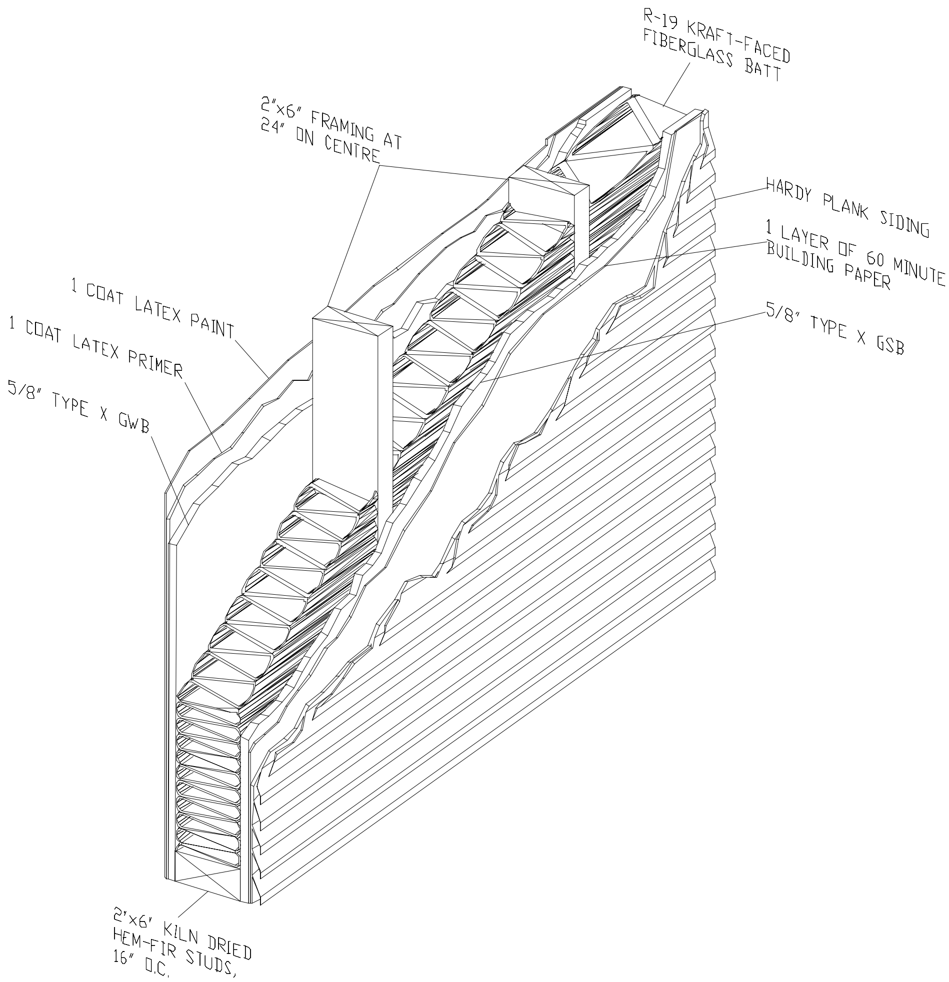


Fig. A32. Post-1984 nonstucco wall 13.

APPENDIX B

Material Properties

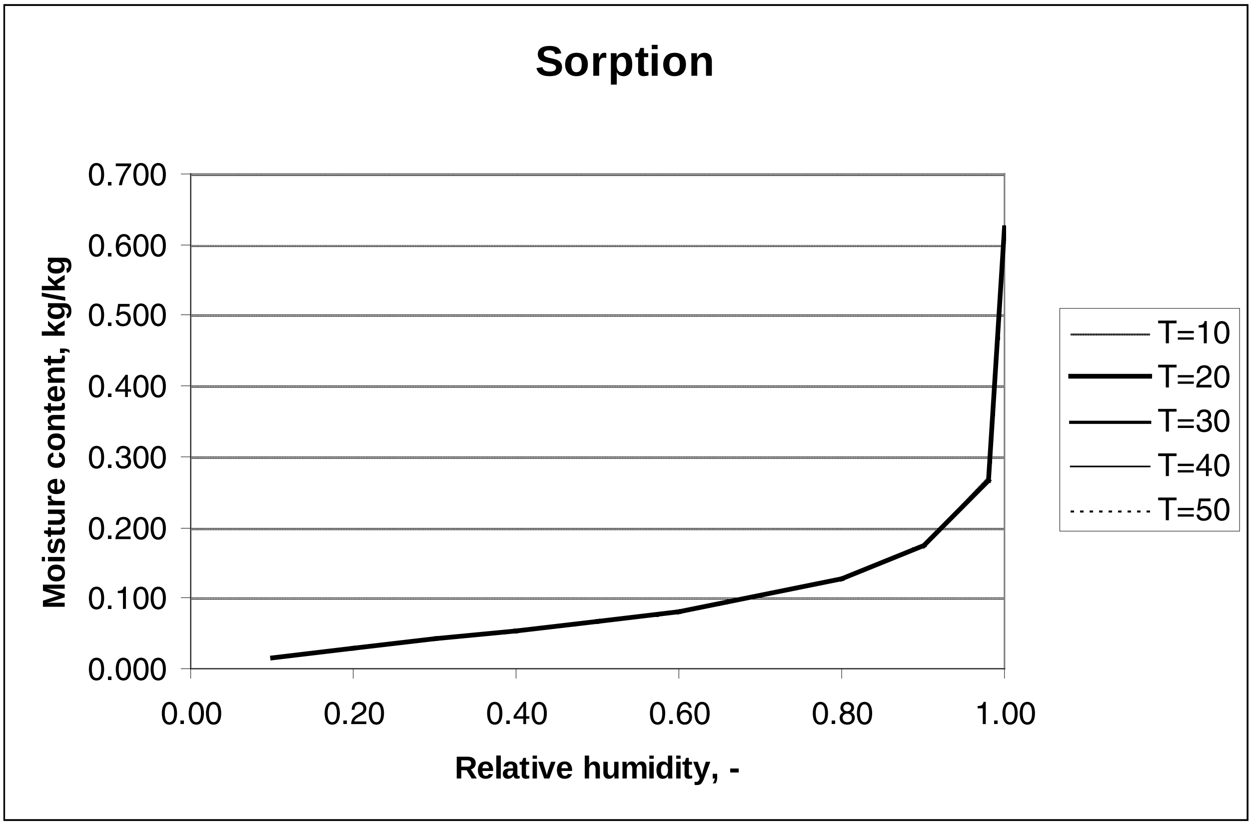


Fig. B1. Sorption isotherm (OSB).

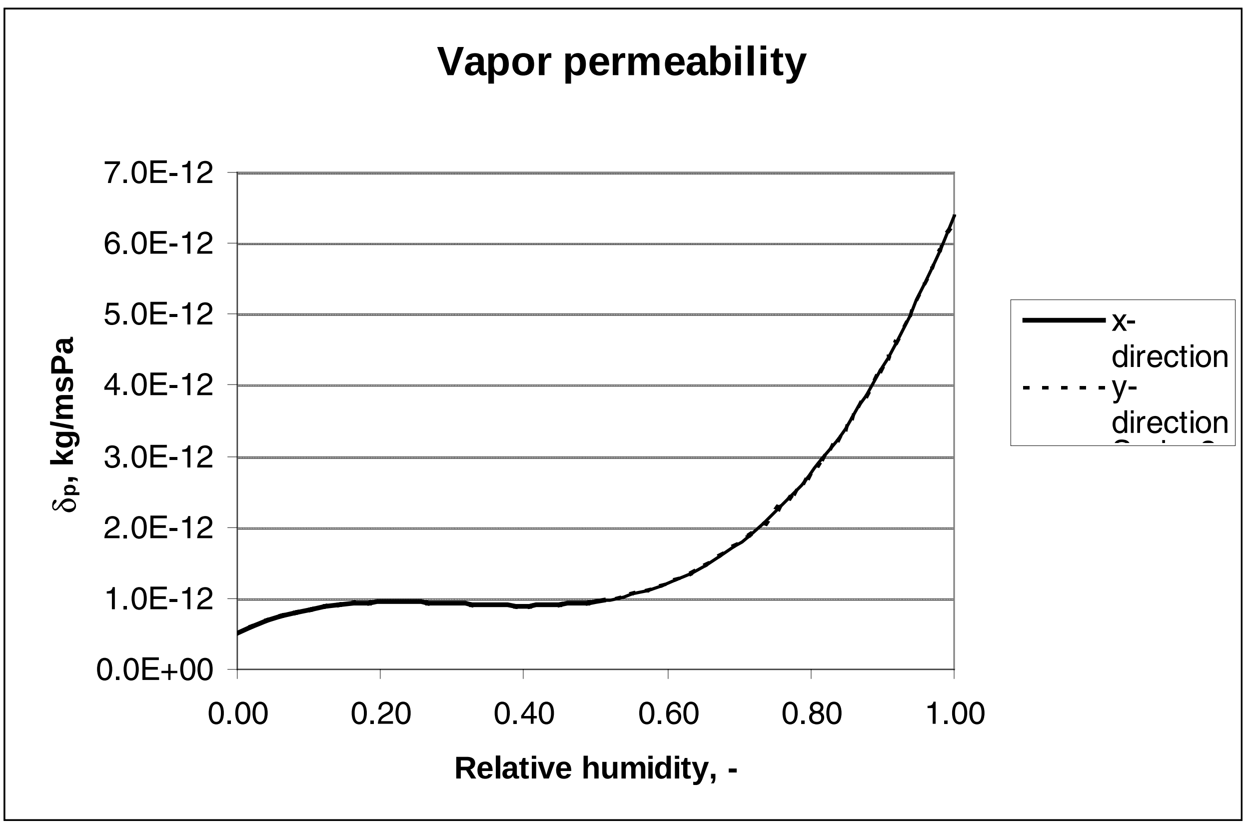


Fig. B2. Vapor permeability (OSB).

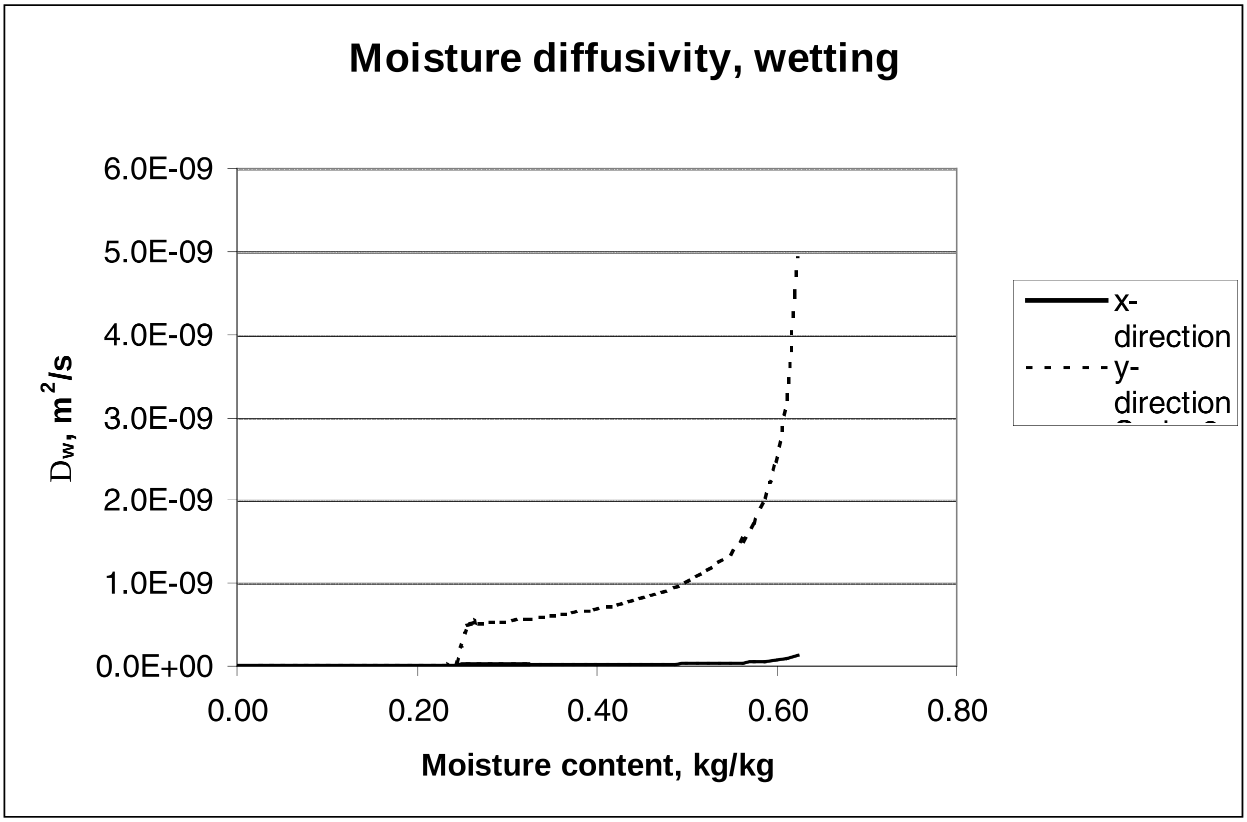


Fig. B3. Liquid diffusivity, wetting (OSB.)

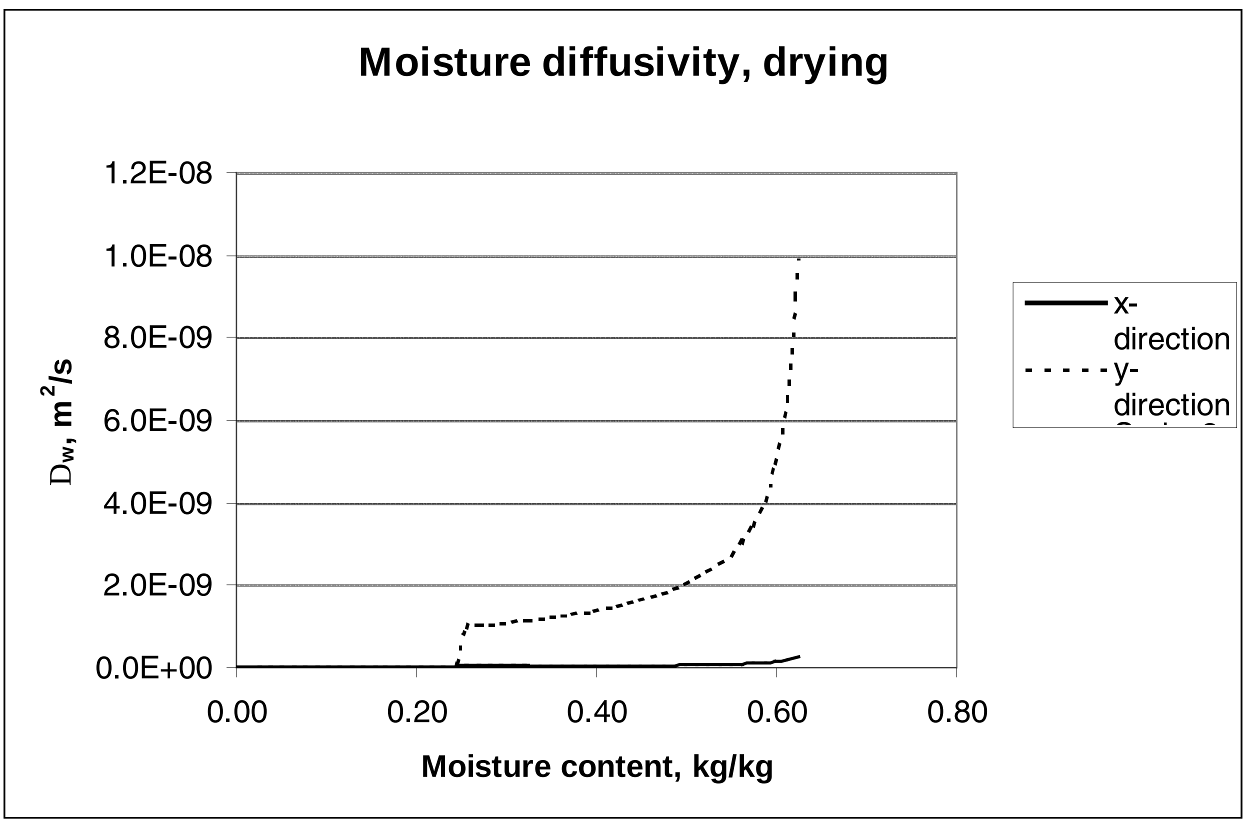


Fig. B4. Liquid diffusivity, drying (OSB).

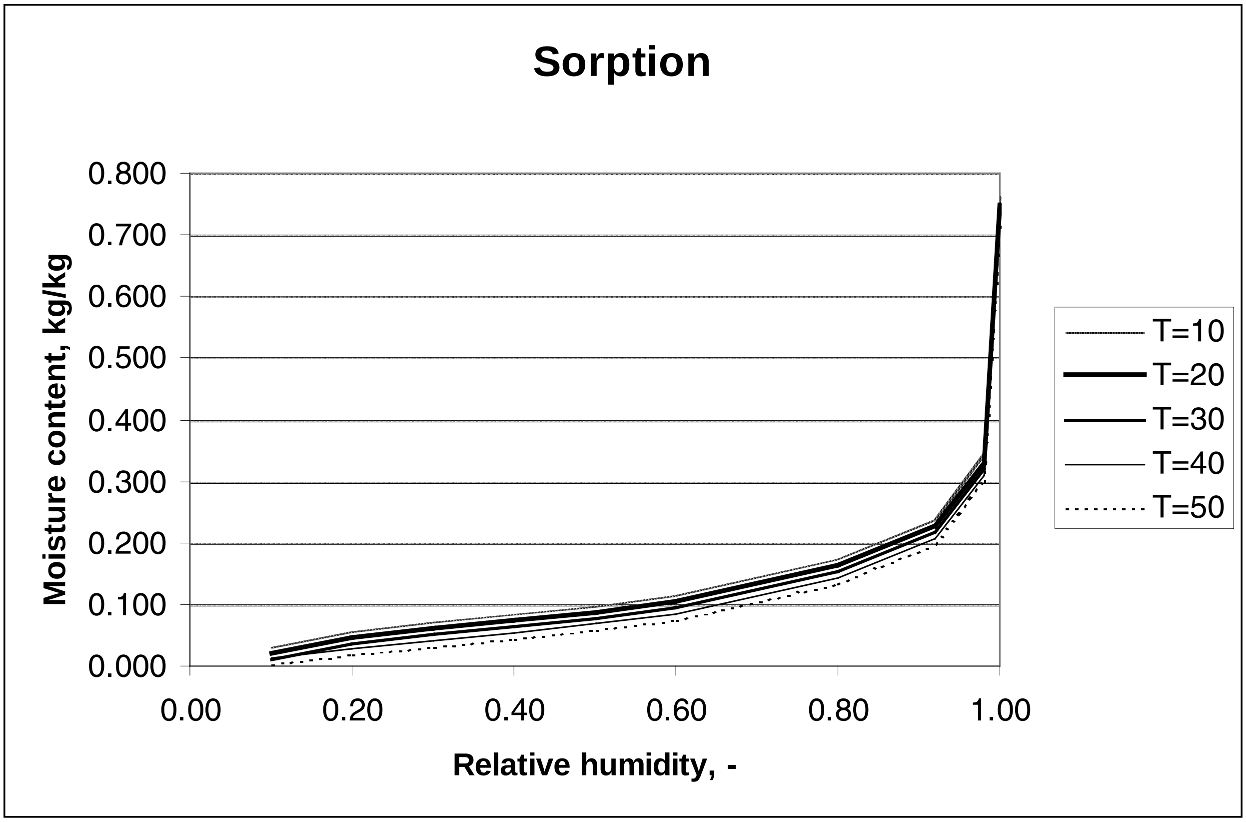


Fig. B5. Sorption isotherm (wood).

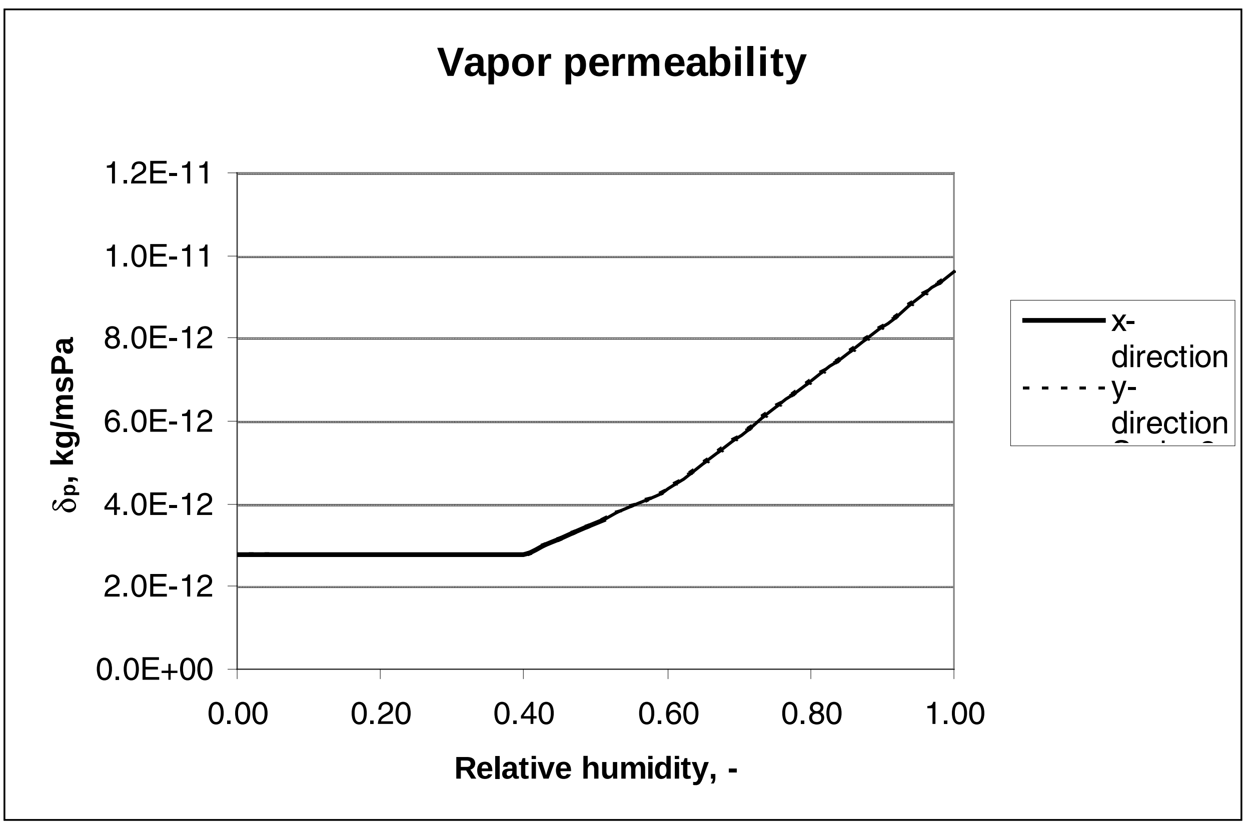
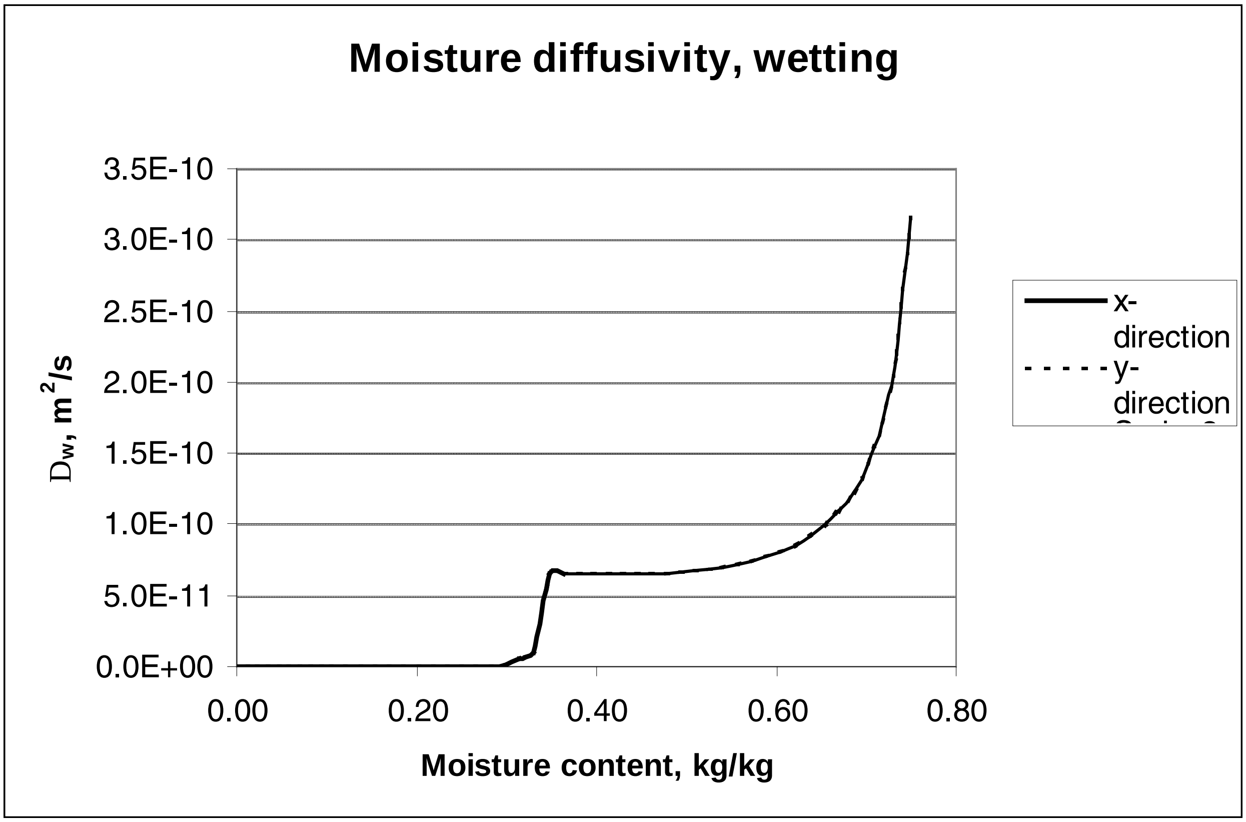


Fig. B6. Vapor permeability (wood).



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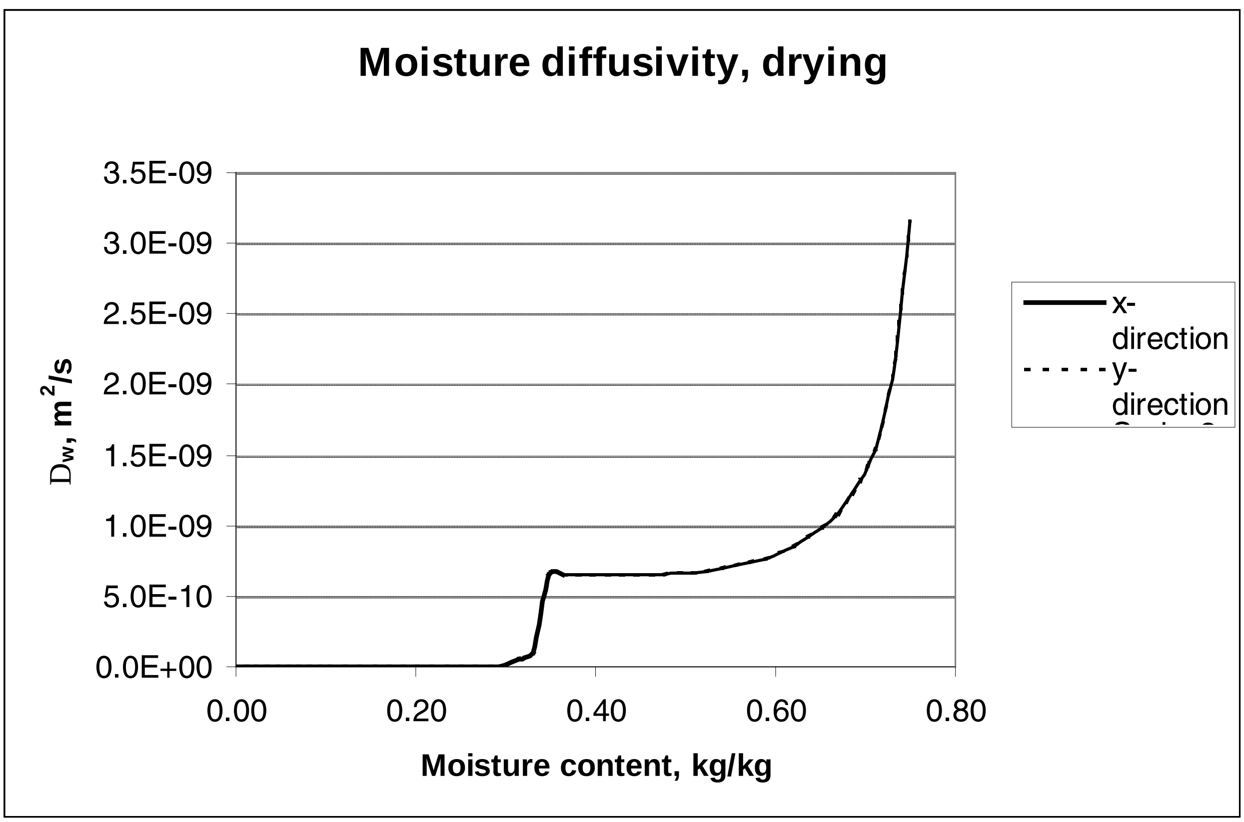

Fig. B8. Liquid diffusivity, drying (wood).

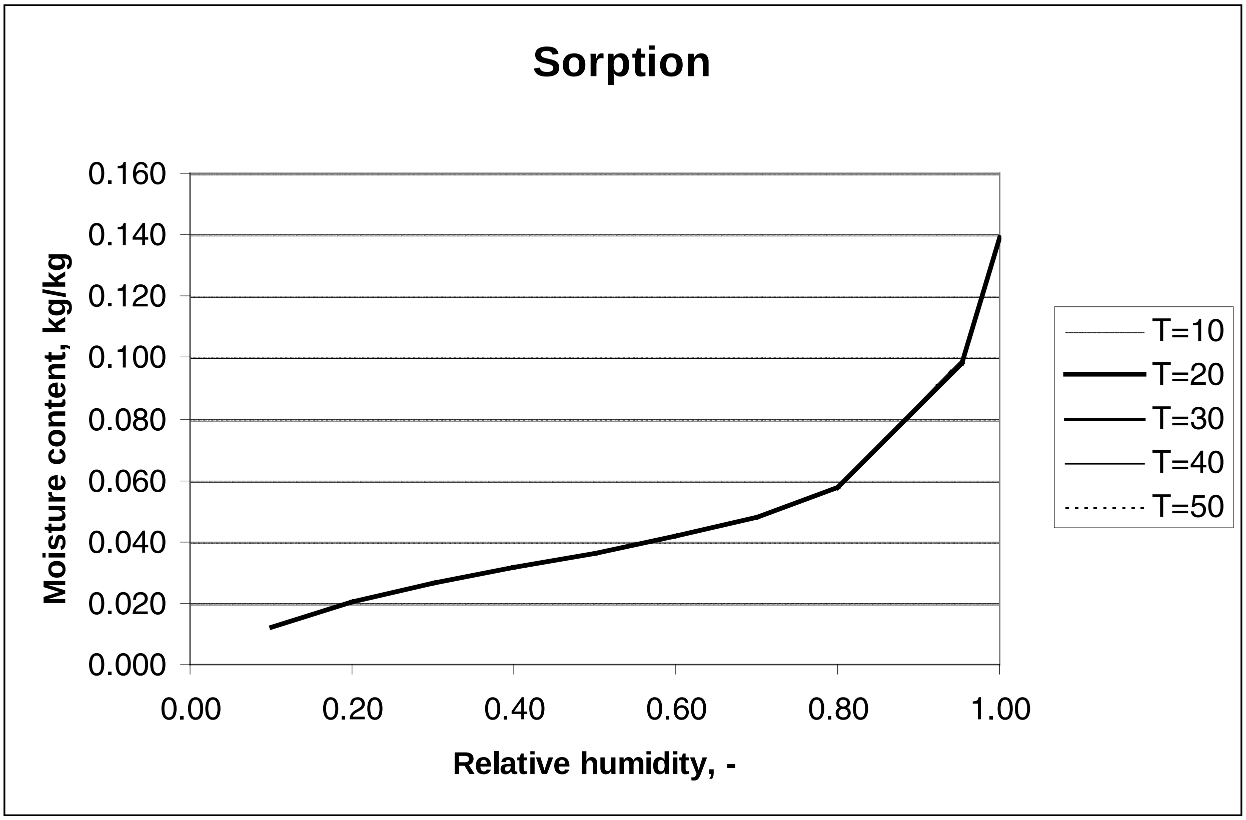

Fig. B9. Sorption isotherm (stucco).

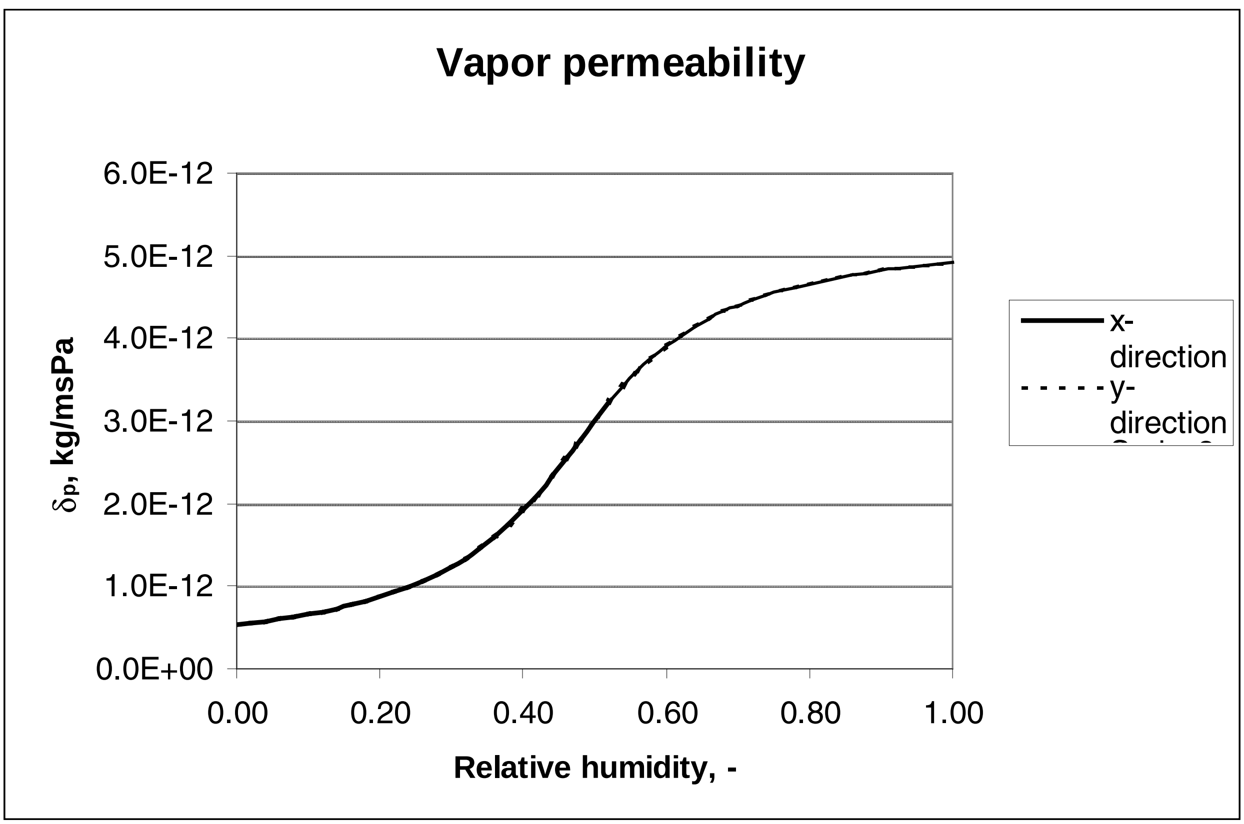

Fig. B10. Vapor permeability (stucco).

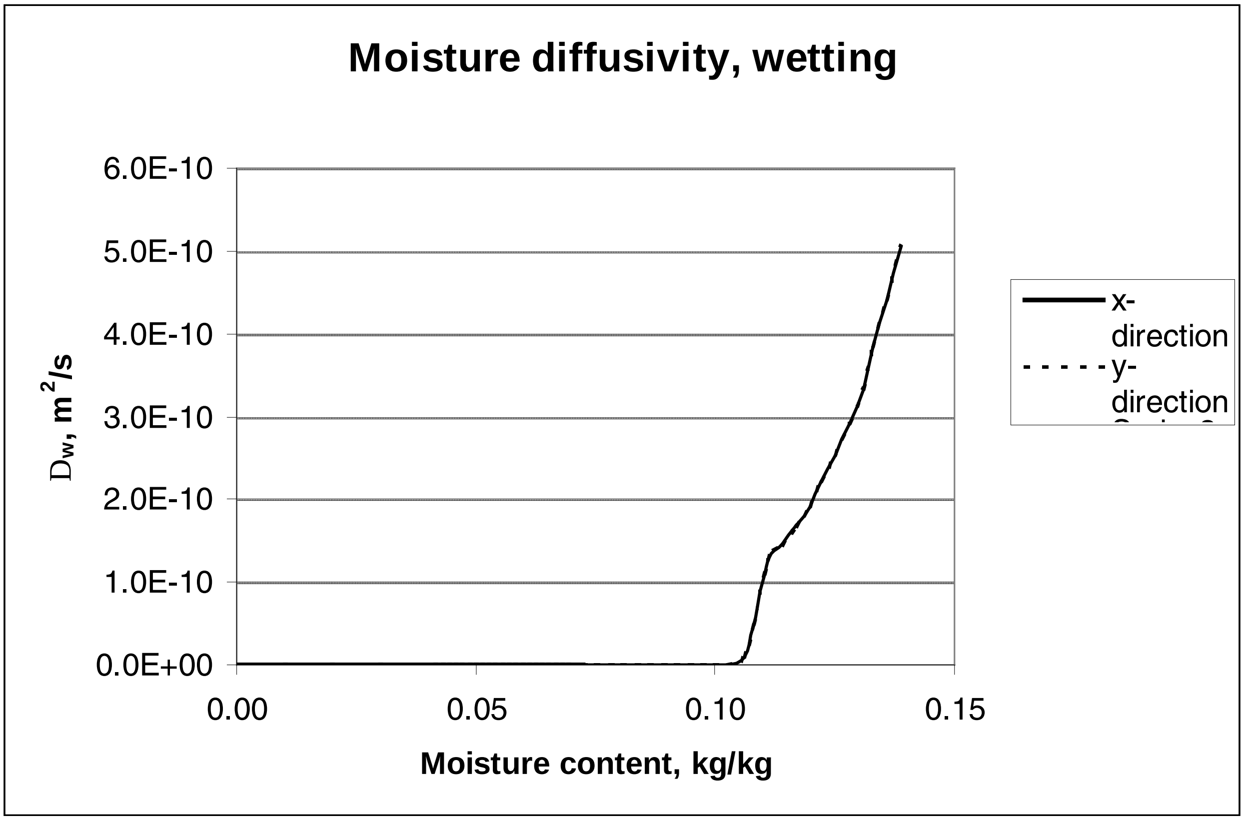

Fig. B11. Liquid diffusivity, wetting (stucco).

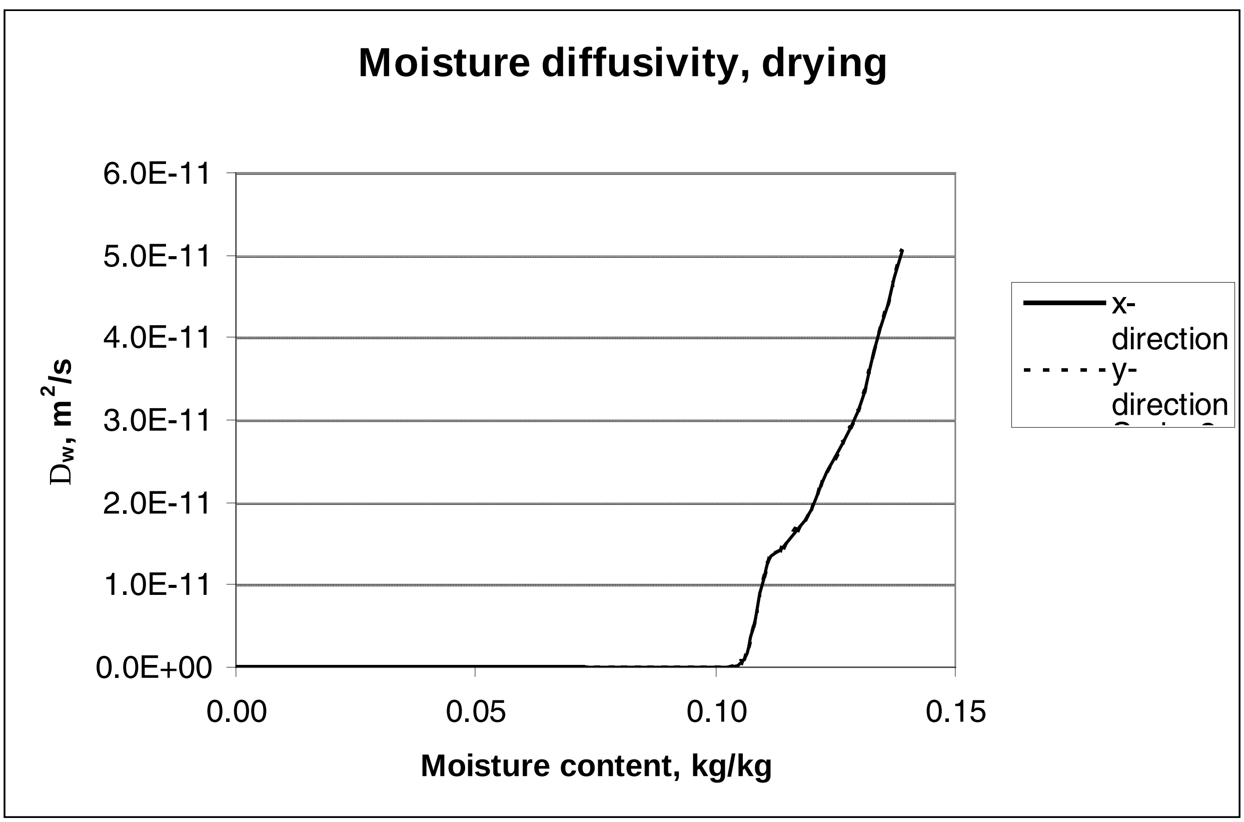

Fig. B12. Liquid diffusivity, drying (stucco).

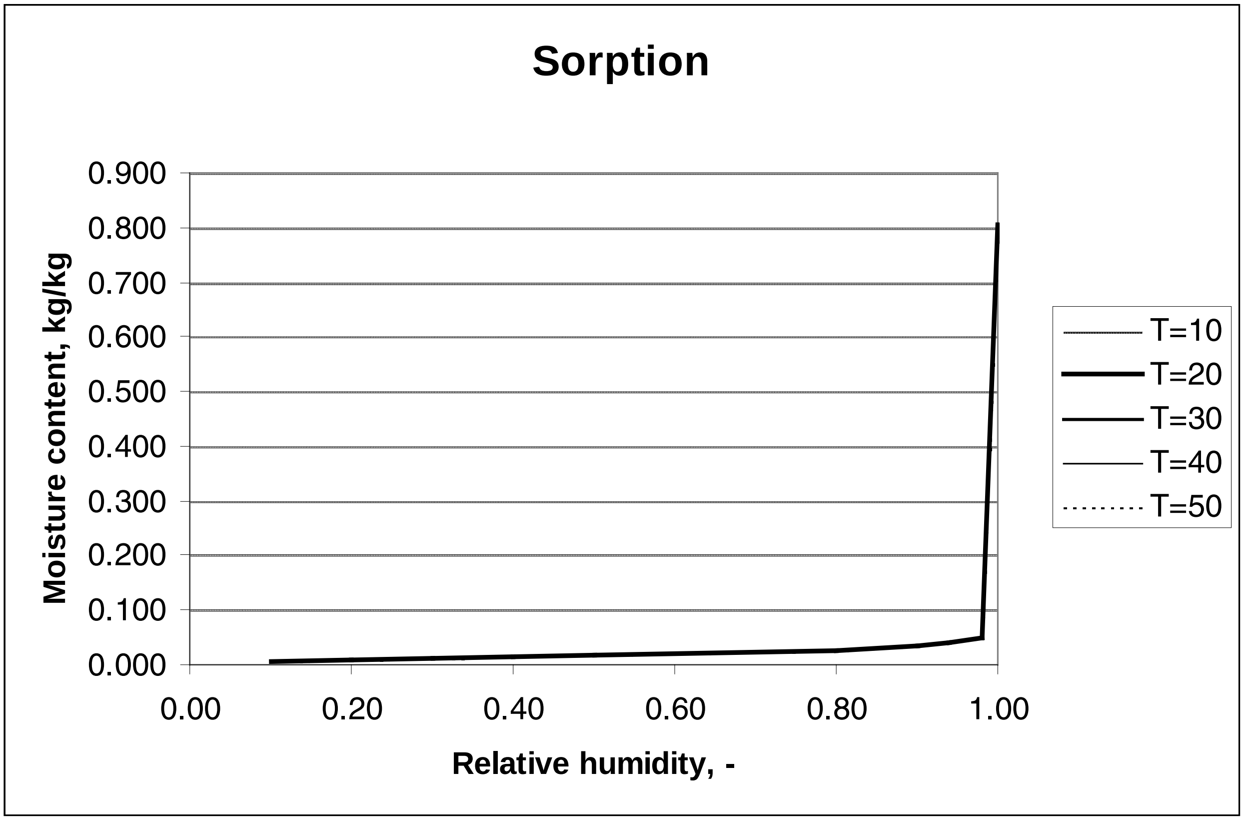

Fig. B13. Sorption isotherm (gypsum).

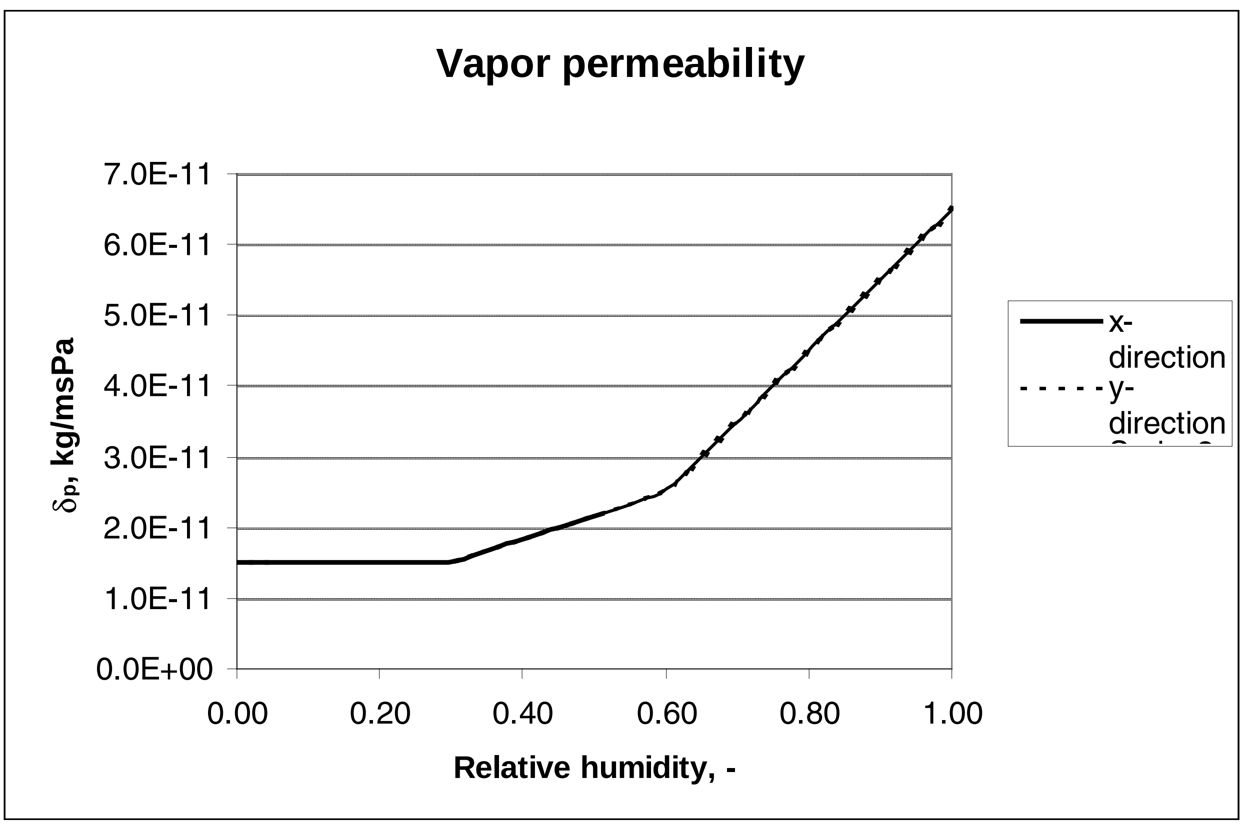

Fig. B14. Vapor permeability (gypsum).

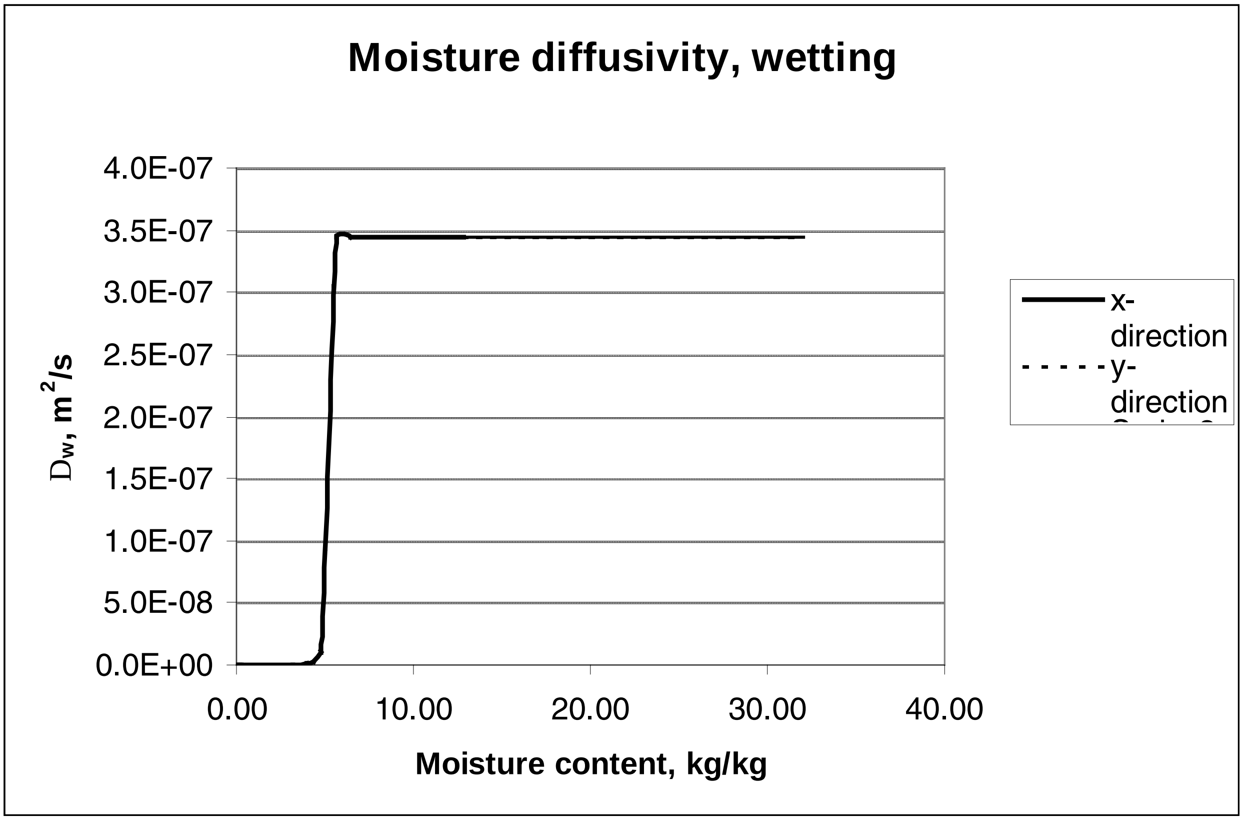

Fig. B15. Liquid diffusivity, wetting (gypsum).

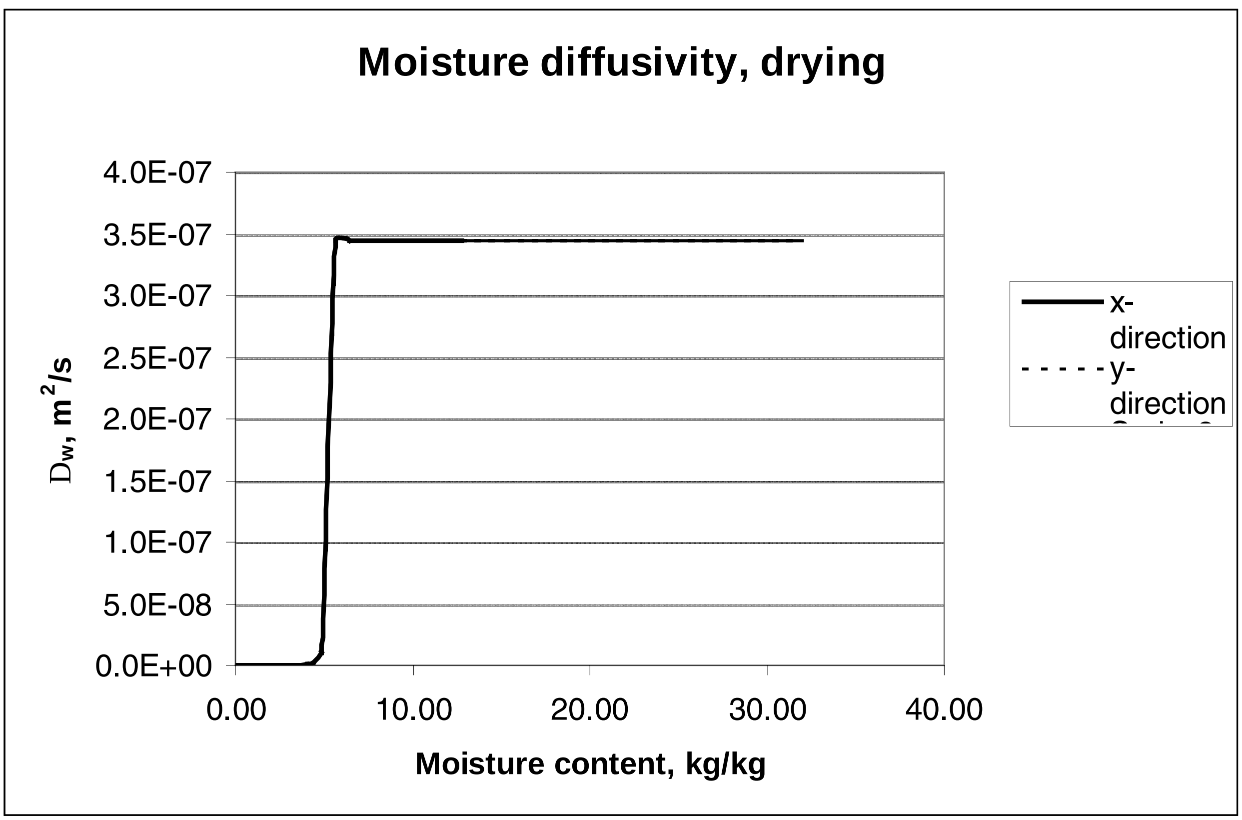

Fig. B16. Liquid diffusivity, drying (gypsum).

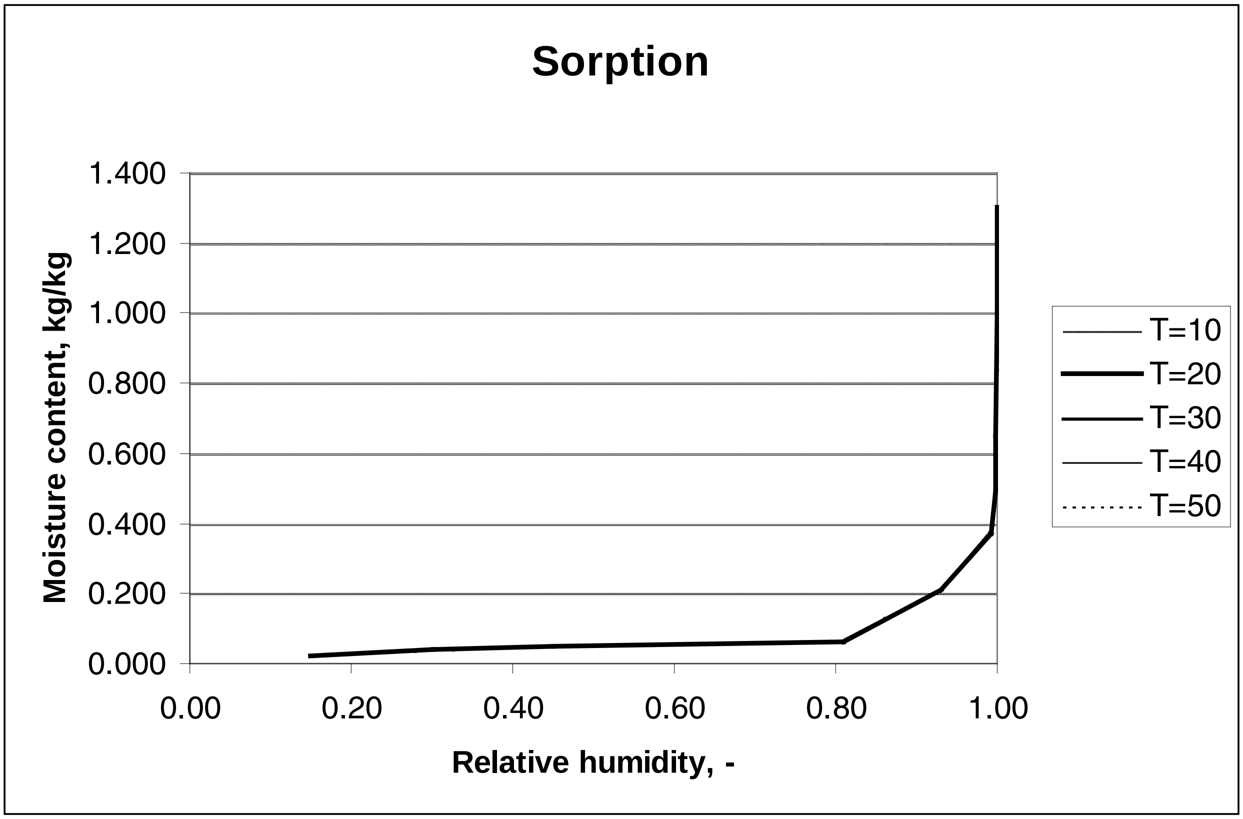

Fig. B17. Sorption isotherm (plywood).

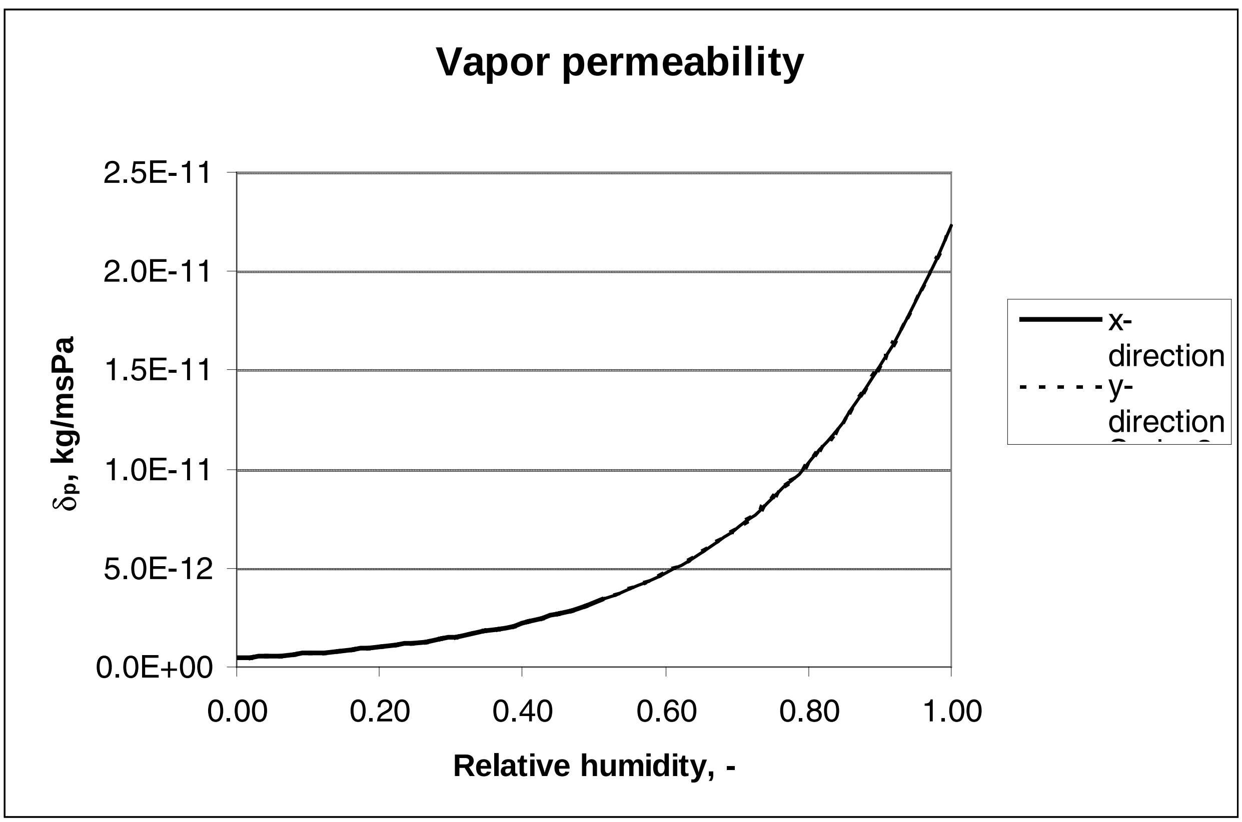

Fig. B18. Vapor permeability (plywood).

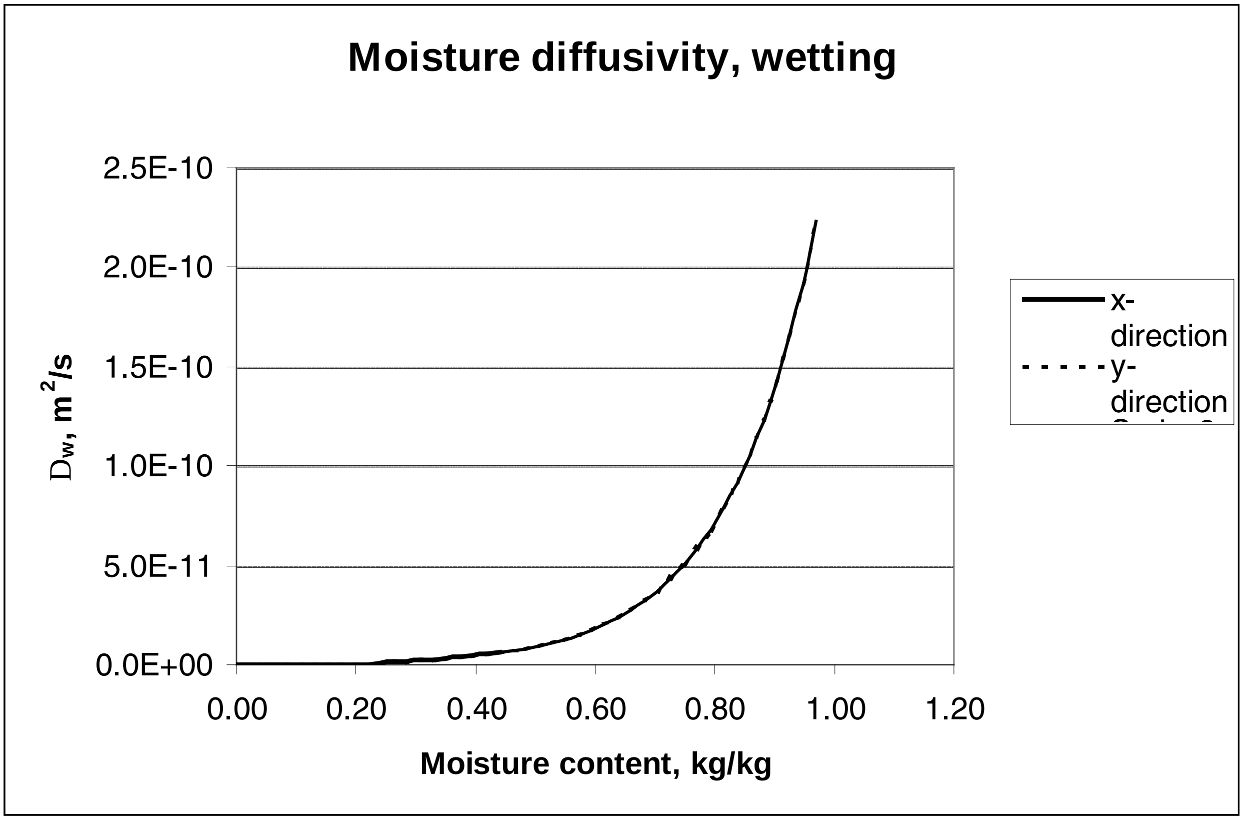

Fig. B19. Liquid diffusivity, wetting (plywood).

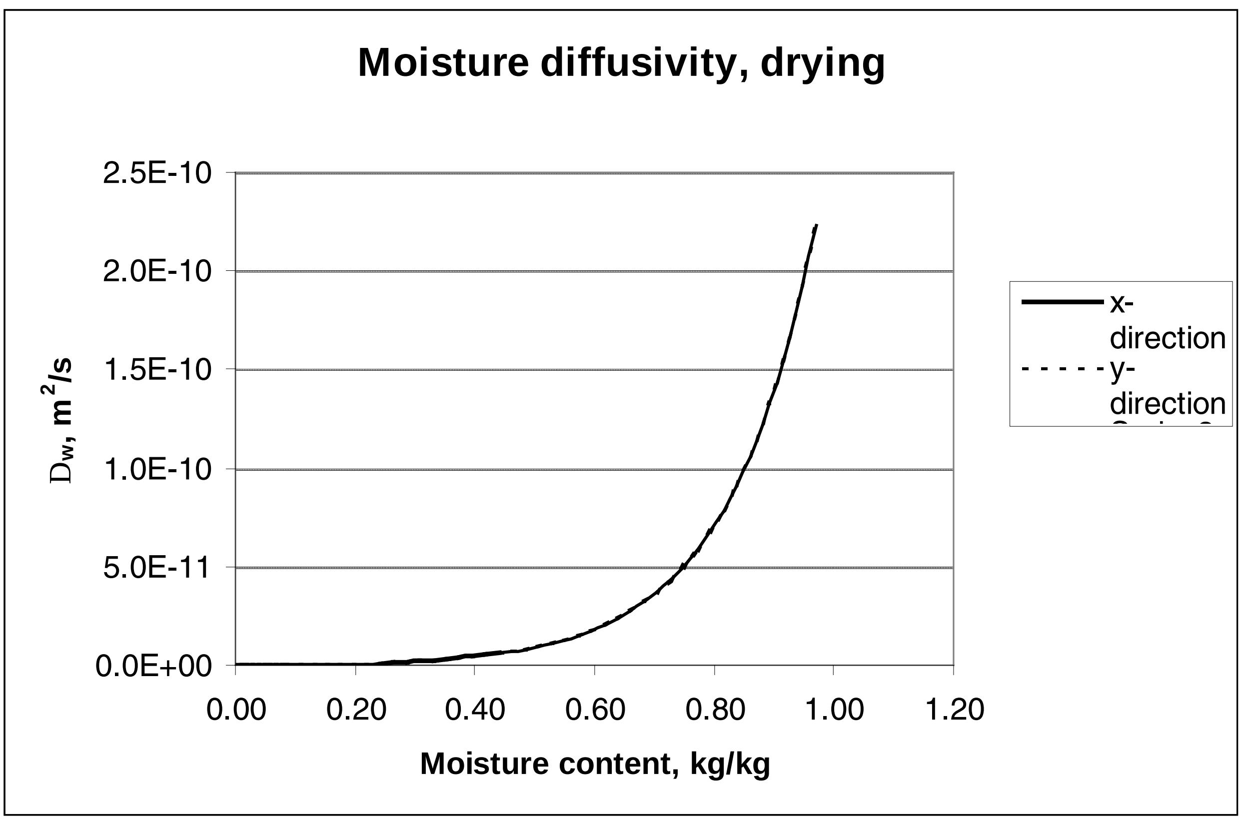

Fig. B20. Liquid diffusivity, drying (plywood).

Table B1. Water vapor permeance of building paper

(ASTM MNL 40, Heinz, 2001)

Material RH (%)	# 15 Felt, Bldg Paper (0.84 mm)	60 min, Bldg Paper (0.35 mm)
50	7.1E-11	7.1E-10
70	1.6E-10	8.5E-10
80	3.0E-10	9.2E-10
90	7.2E-10	9.8E-10

APPENDIX C

HYGROTHERMAL RESULTS

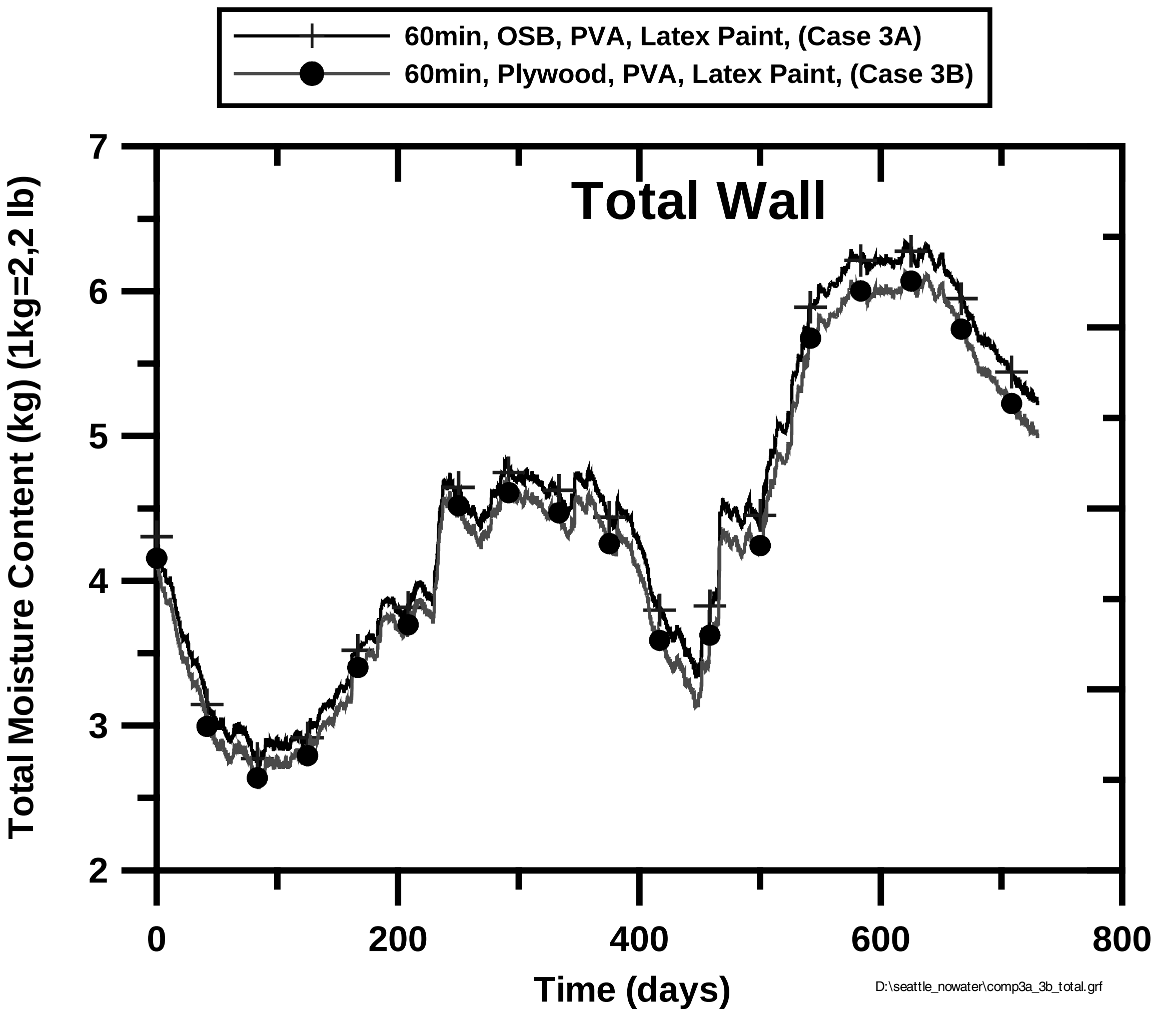

Fig. C1. Effect of sheathing board on total moisture distribution (walls 3A and 3B).

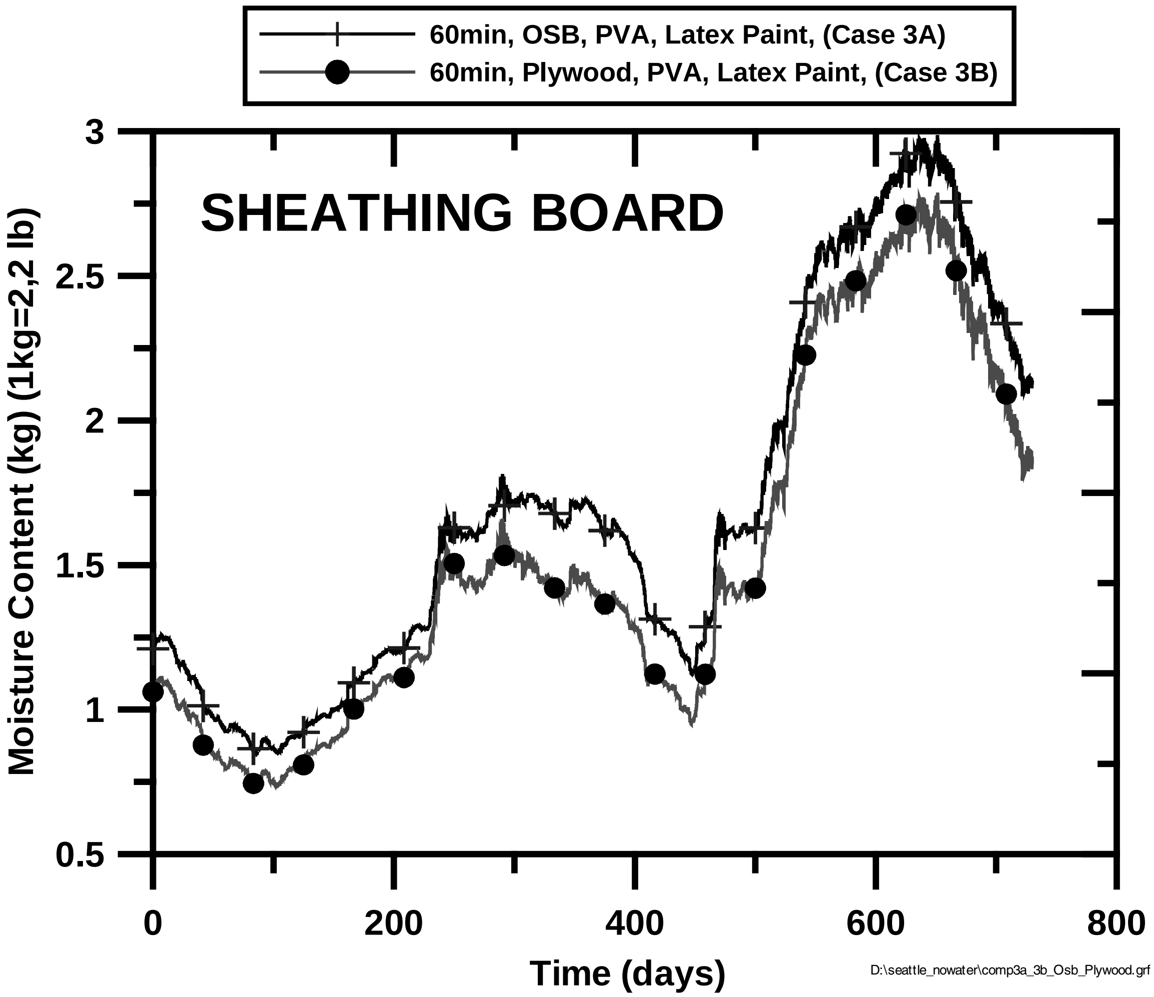

Fig. C2. Effect of sheathing board on sheathing moisture distribution (walls 3A and 3B).

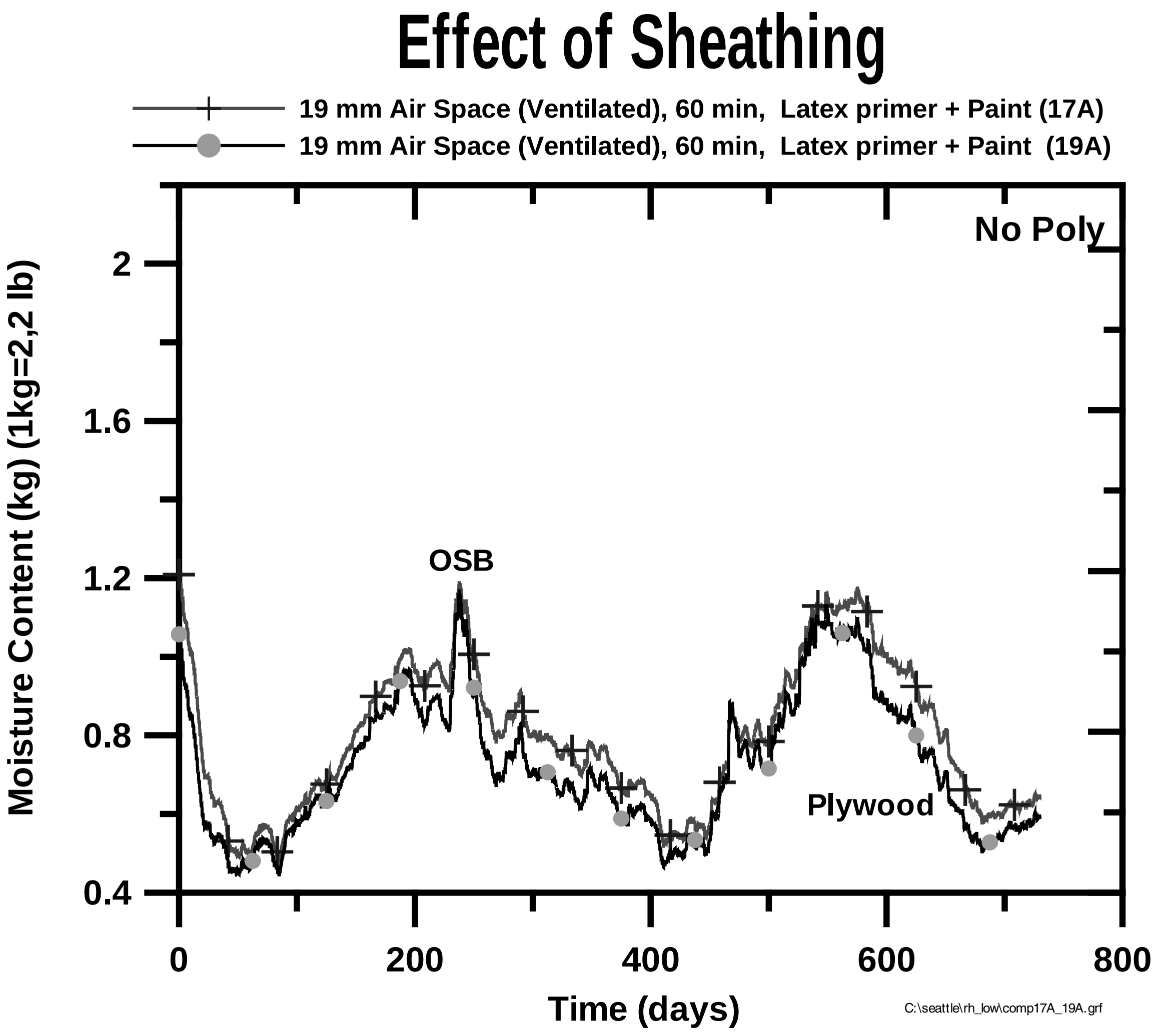

Fig. C3. Effect of sheathing board on sheathing moisture distribution (walls 17A and 19A).

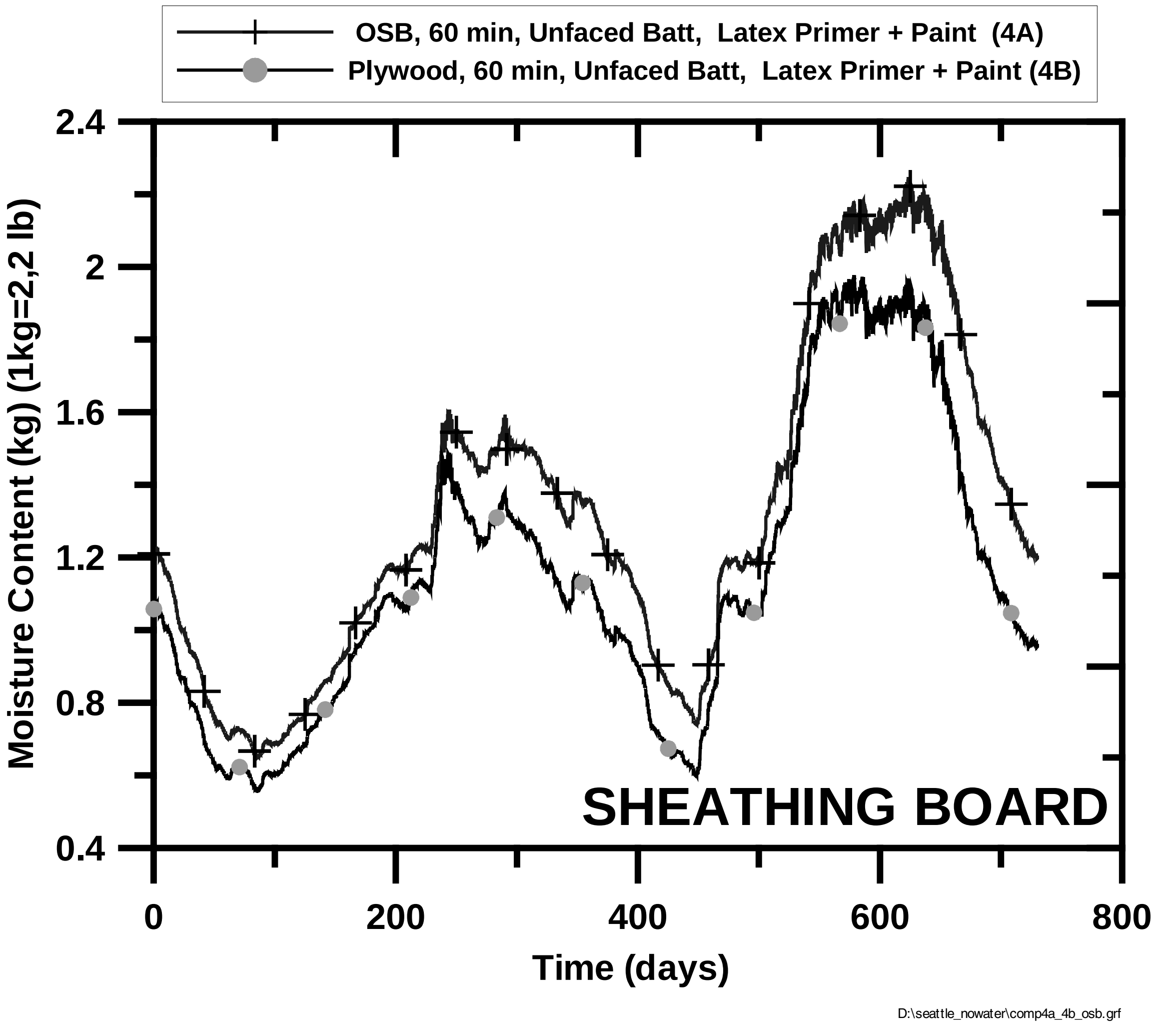

Fig. C4. Effect of sheathing board on sheathing moisture distribution (walls 4A and 4B).

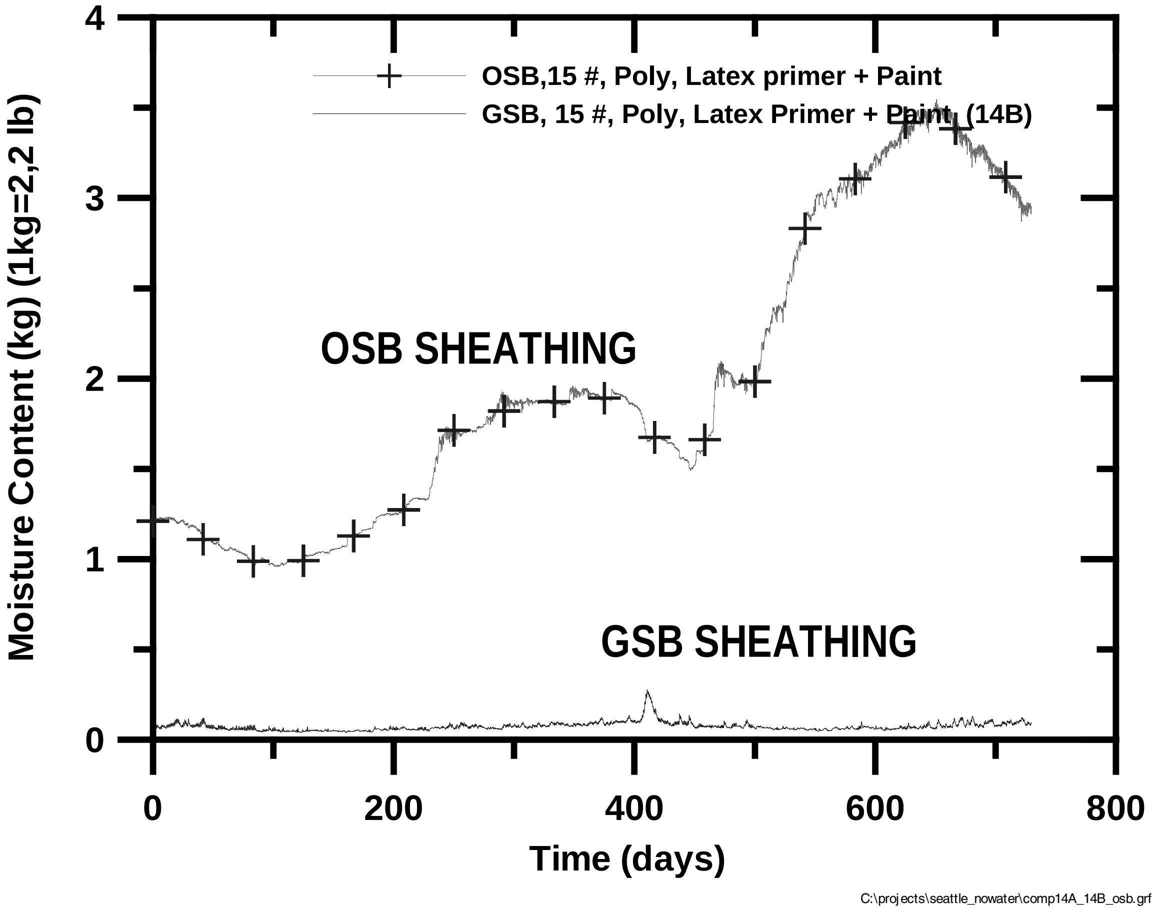

Fig. C5. Effect of sheathing board on sheathing moisture distribution.

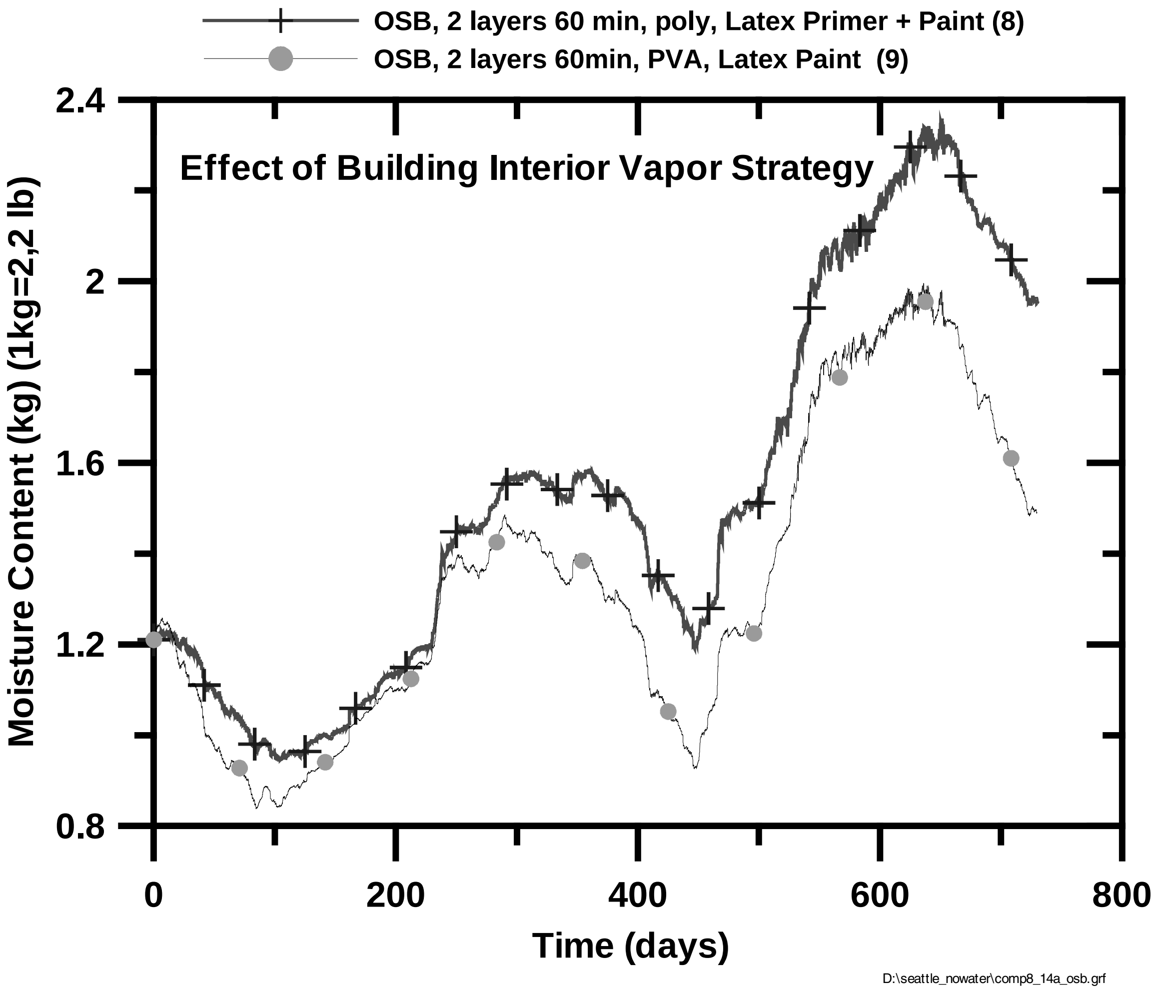

Fig. C6. Effect of interior vapor control on sheathing moisture distribution (walls 8 and 9).

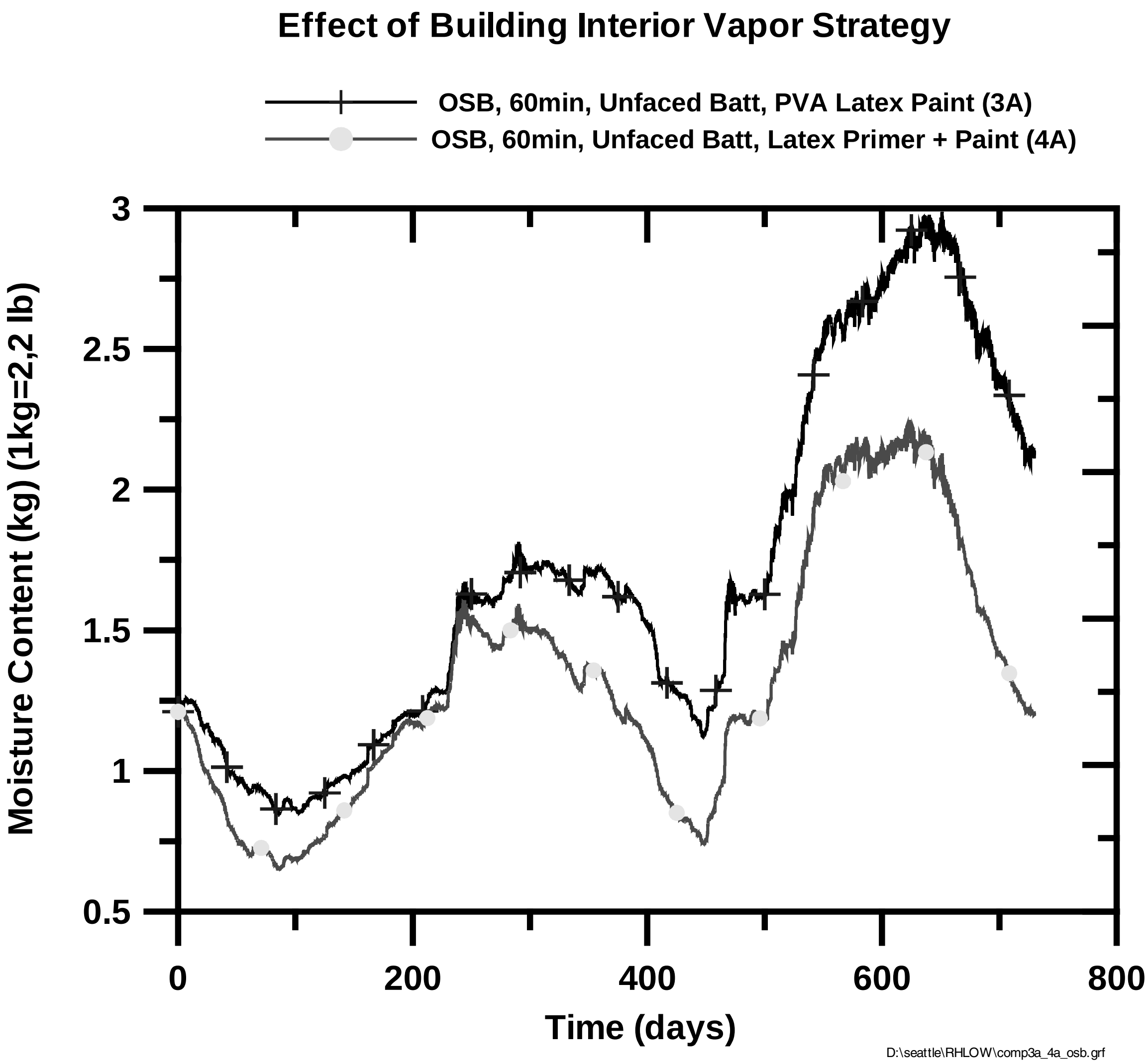

Fig. C7. Effect of interior vapor control on sheathing moisture distribution (walls 3A and 4A).

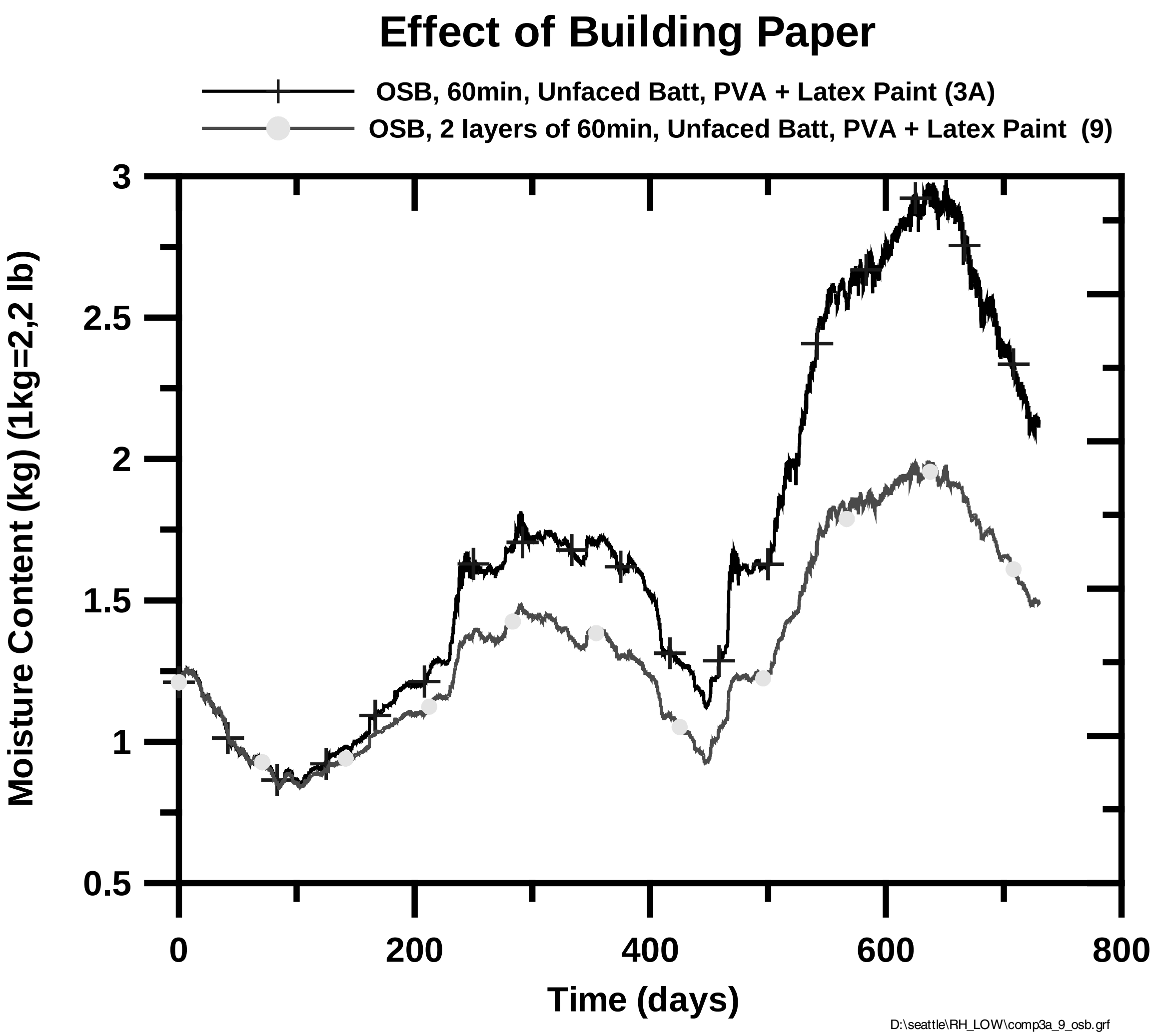

Fig. C8. Effect of building paper on sheathing moisture distribution (walls 3A and 4A).

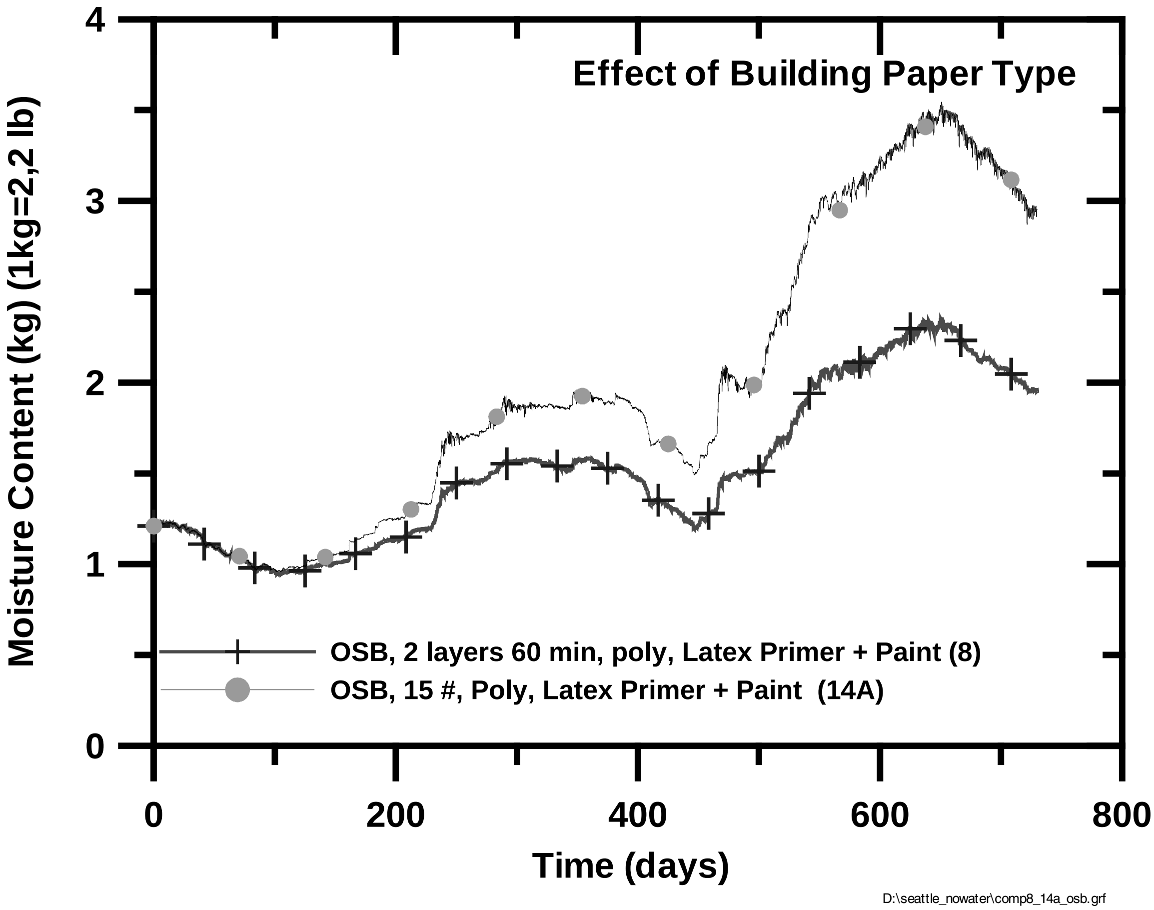

Fig. C9. Effect of building paper type on OSB sheathing moisture distribution (walls 8 and 14A).

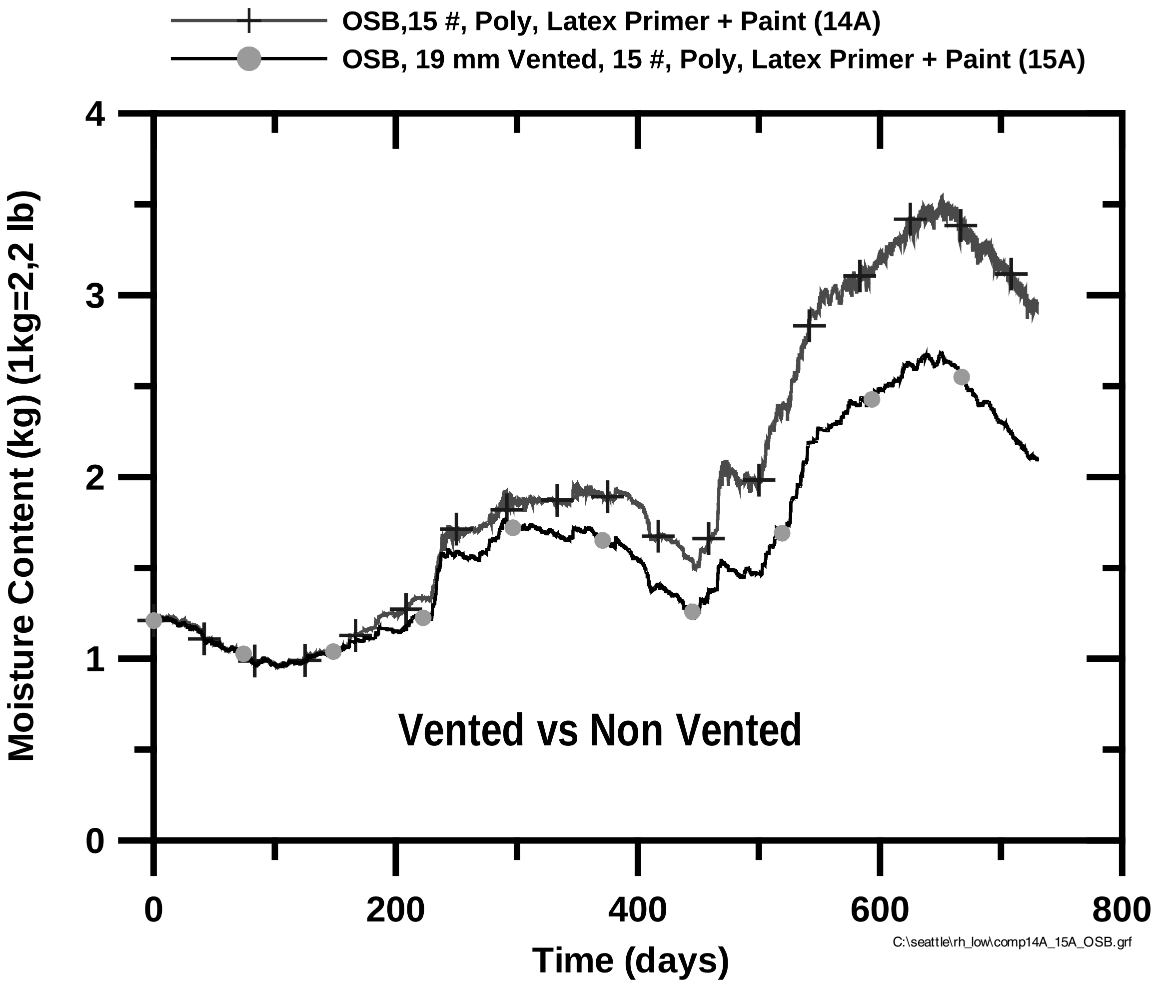

Fig. C10. Effect of vented vs nonvented wall on OSB sheathing moisture distribution (walls 14A and 15A).

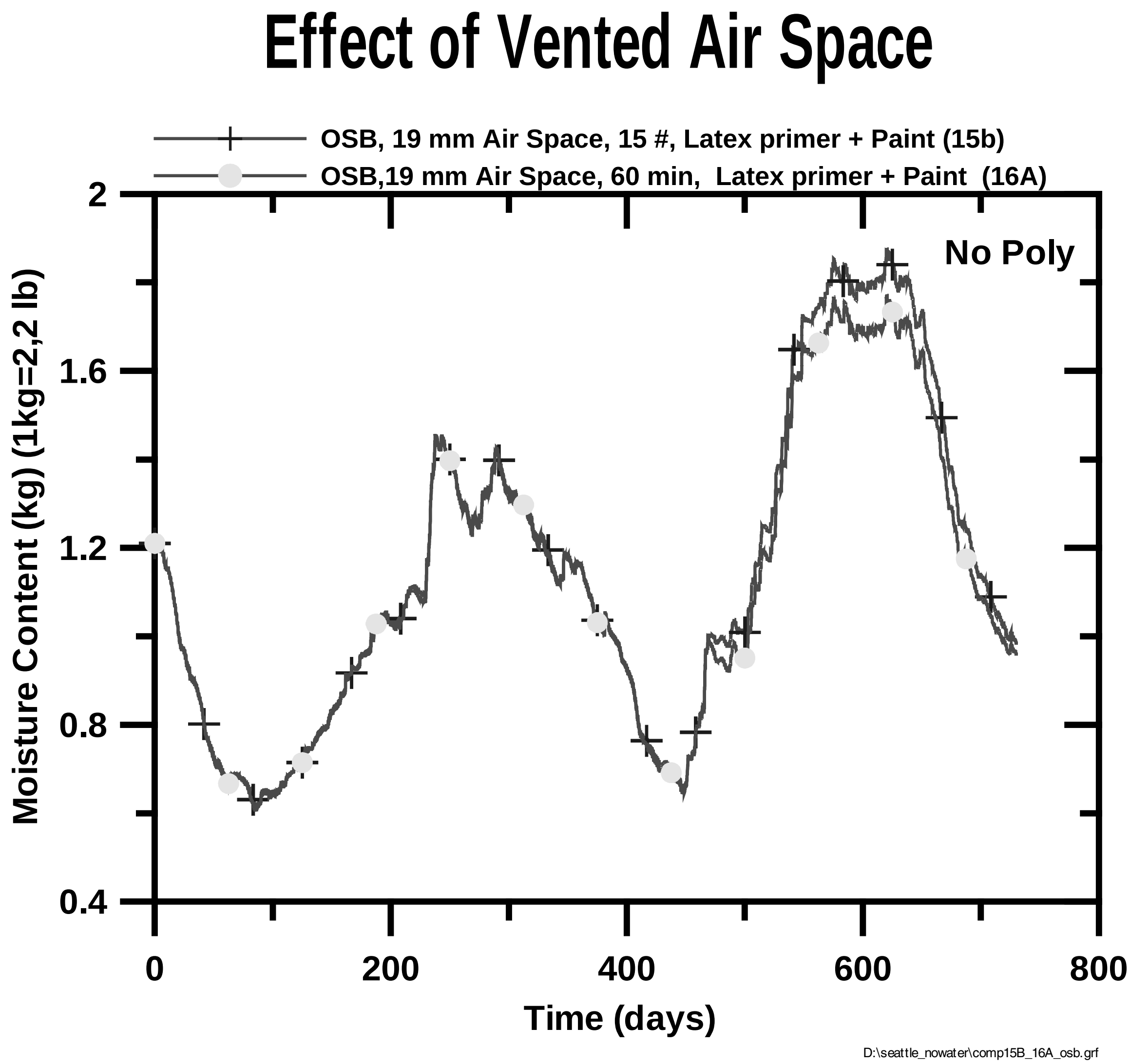

Fig. C11. Effect of vented walls on OSB sheathing moisture distribution (walls 14A and 15A).

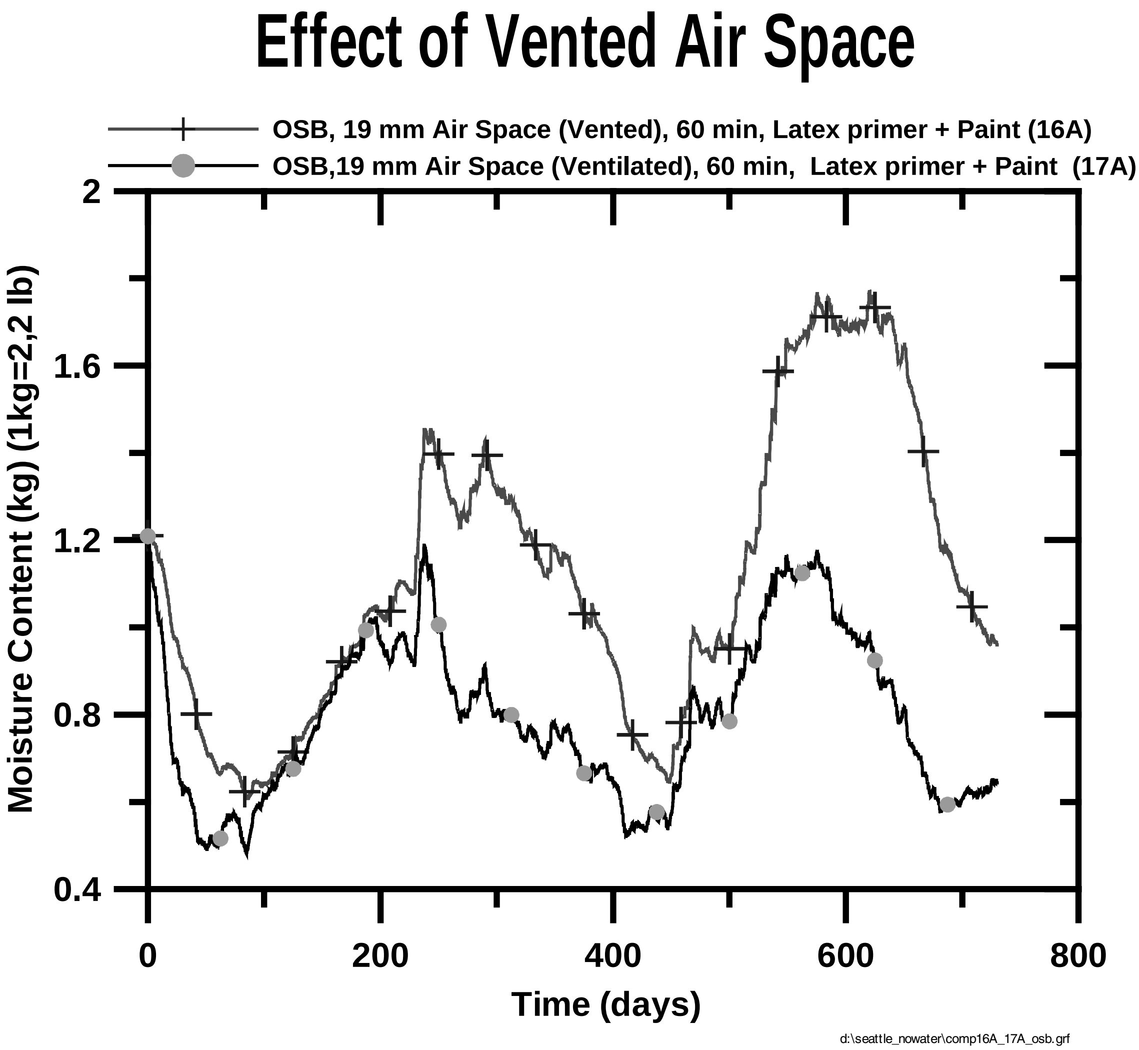

Fig. C12. Effect of ventilation strategy of stucco walls on OSB sheathing moisture distribution (walls 16A and 17A).

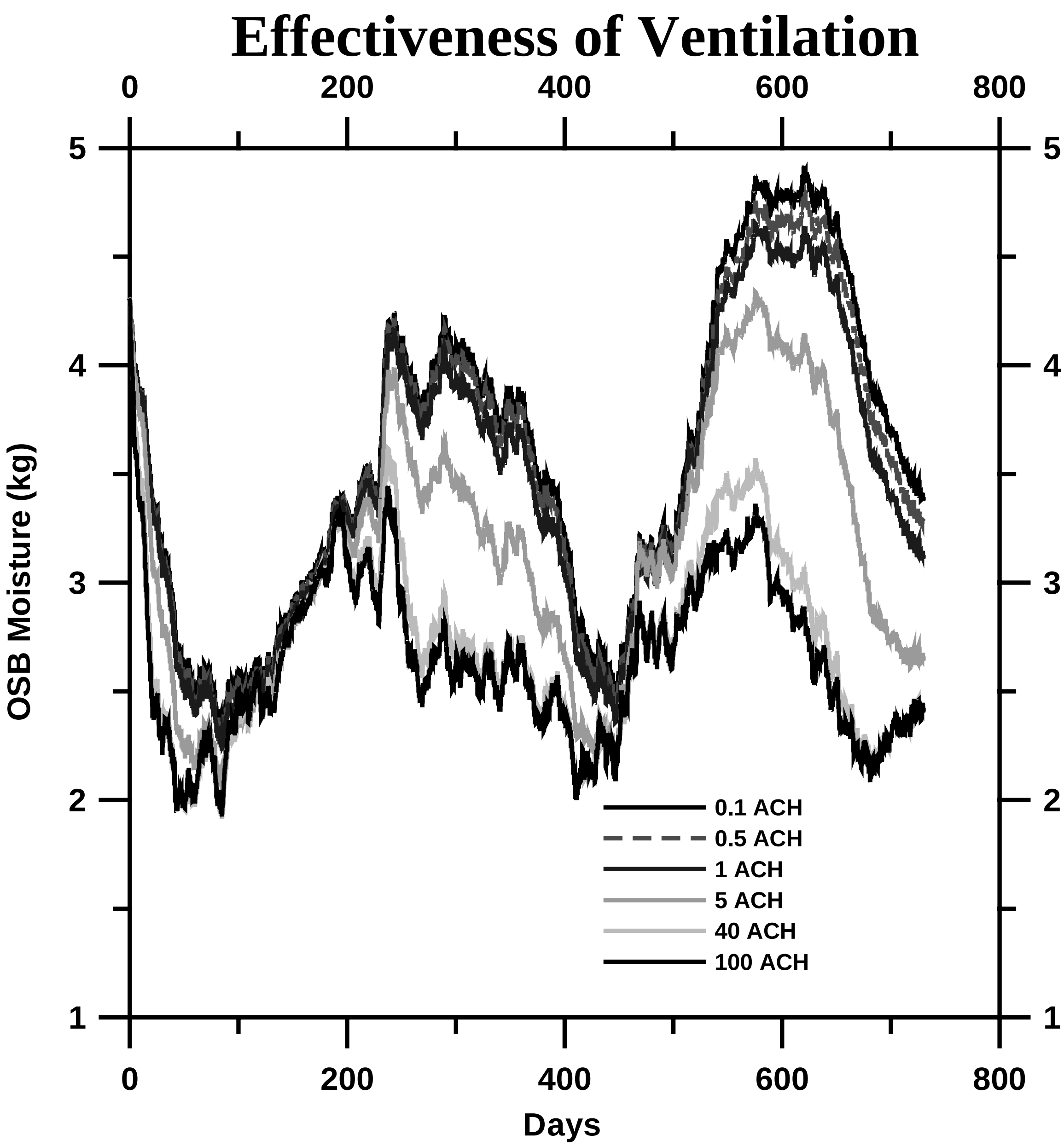

Fig. C13. Effectiveness of ventilation on OSB sheathing board.

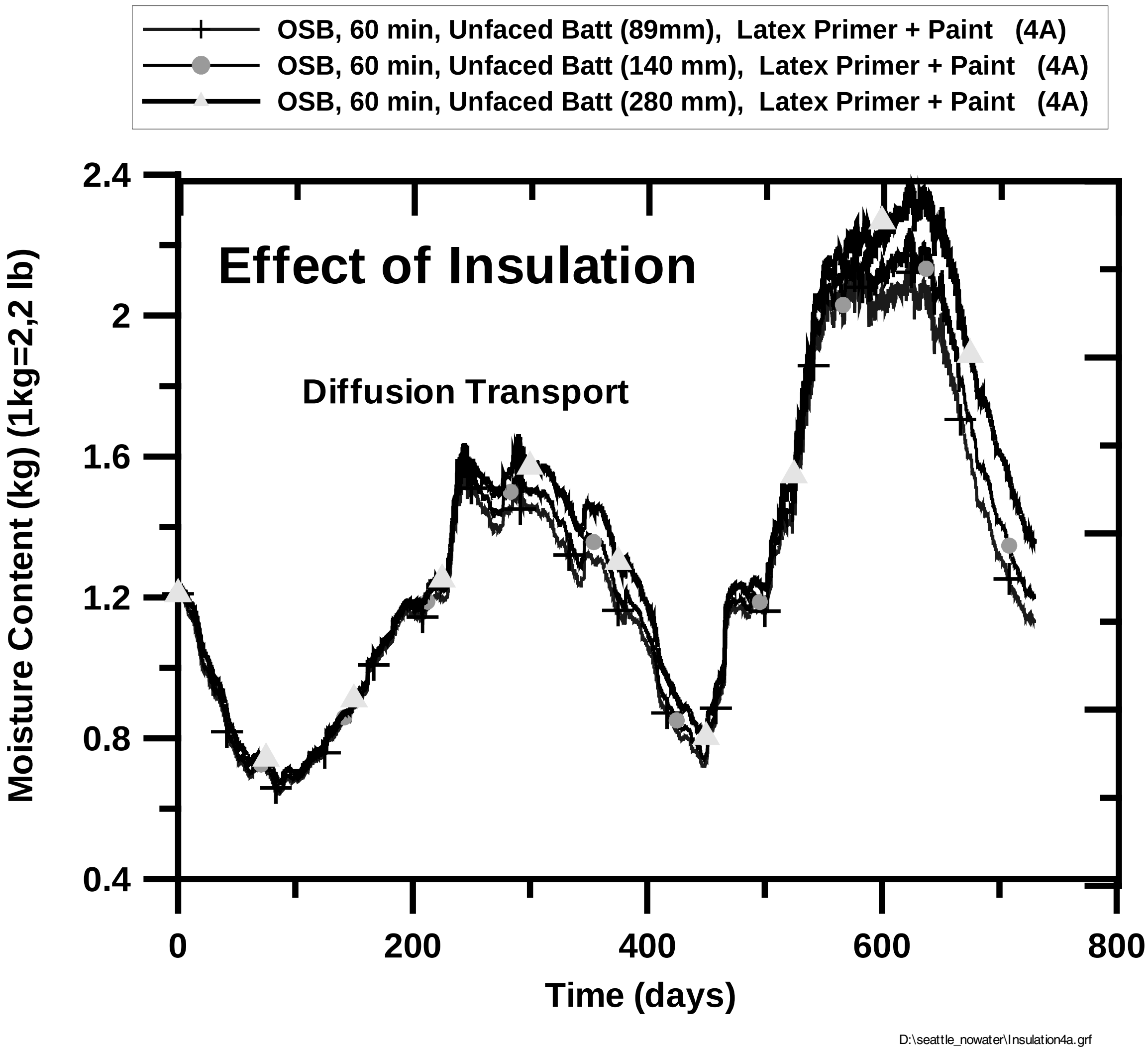

Fig. C14. Effect of insulation level on moisture performance of OSB layer (wall 4A).

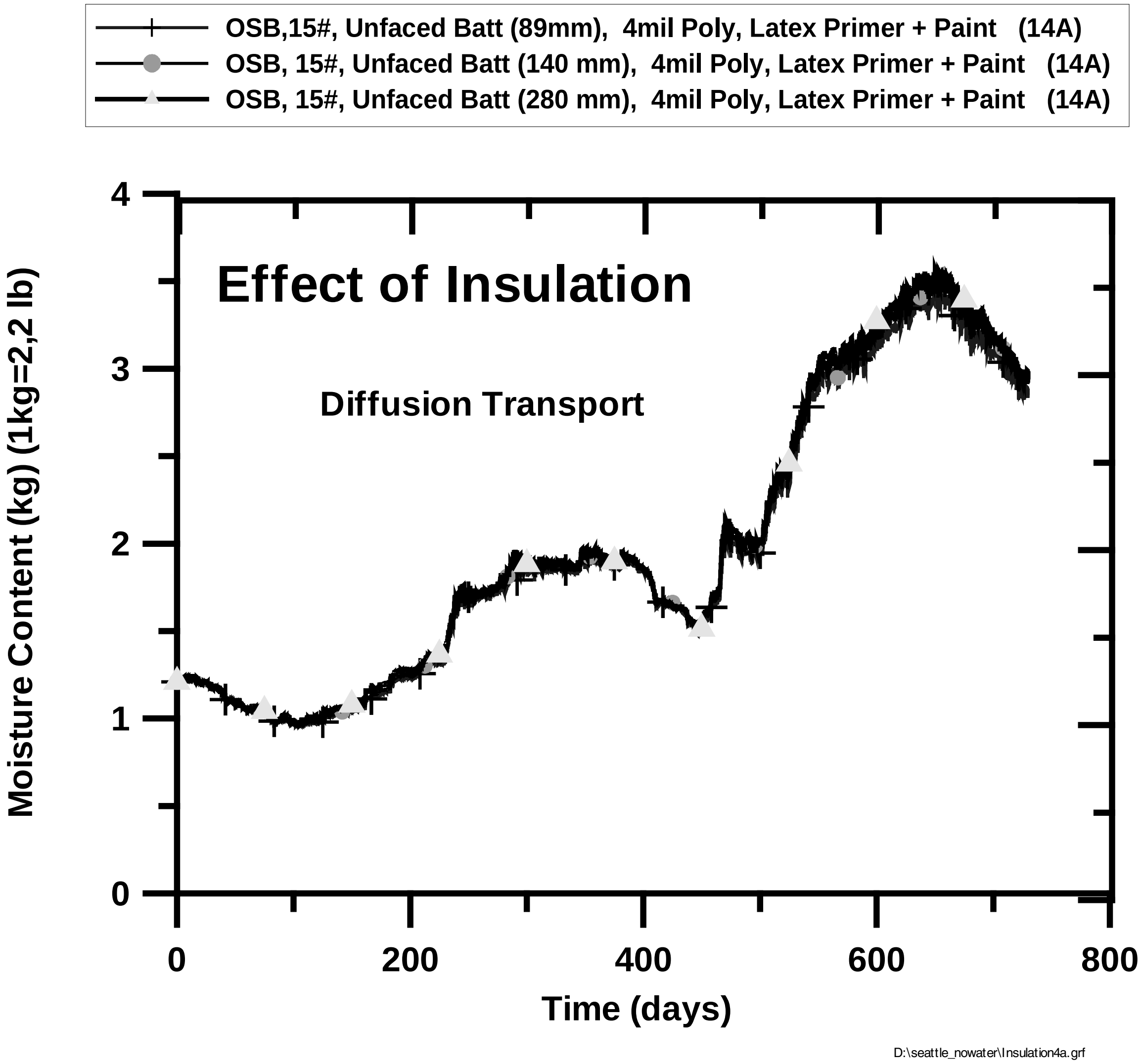

Fig. C15. Effect of insulation level on moisture performance of OSB layer (14A).

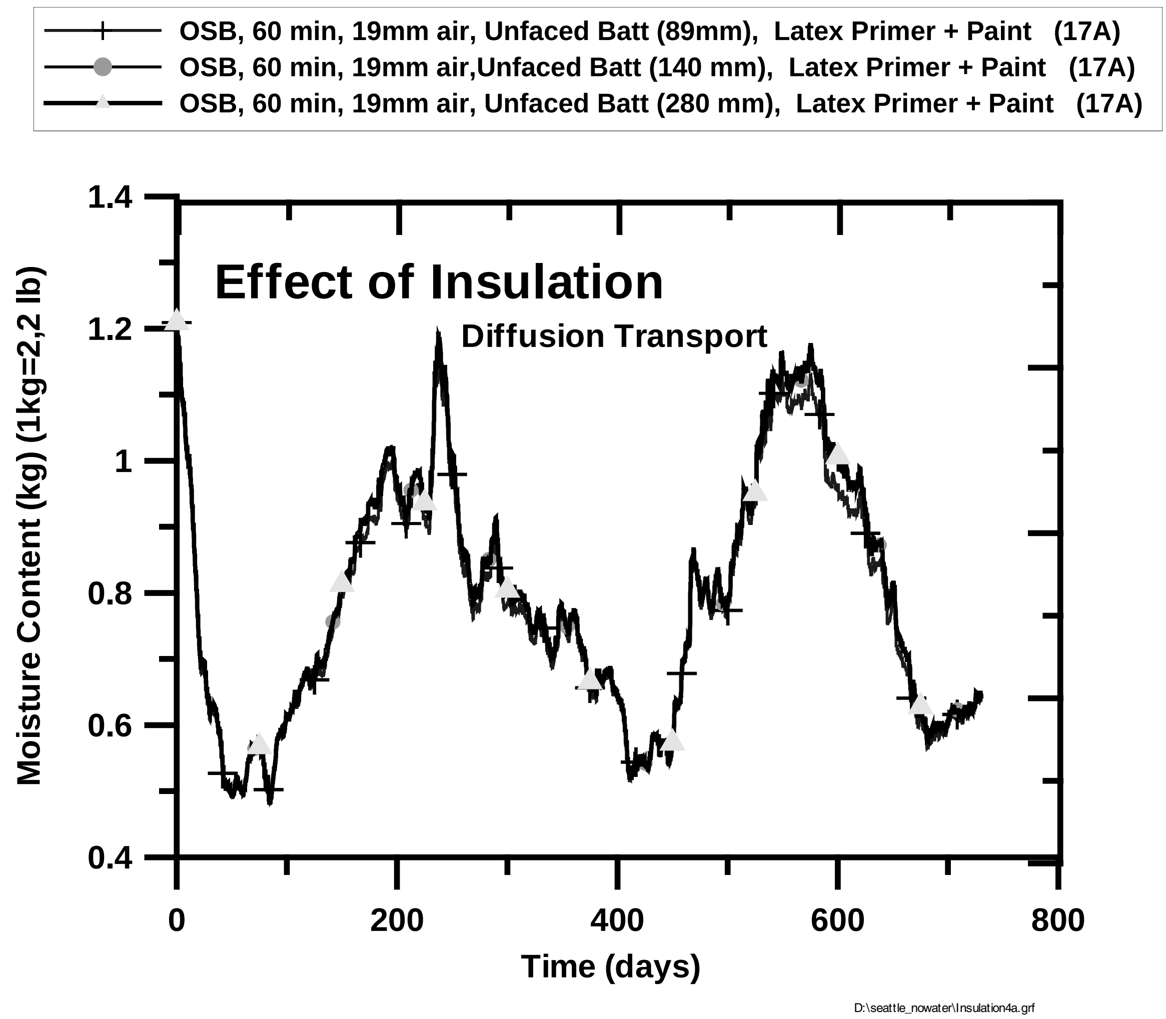

Fig. C16. Effect of insulation level on moisture performance of OSB layer (17A).

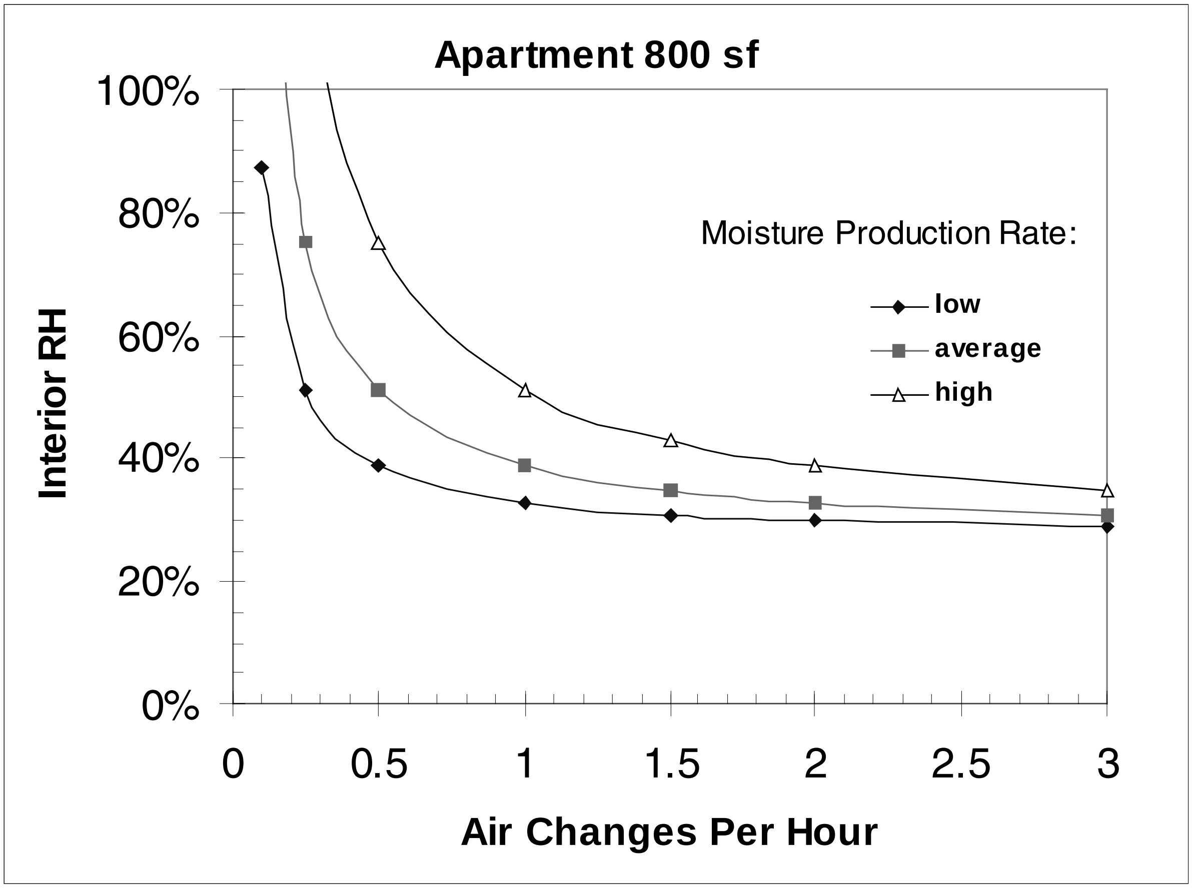

Fig. C17. Interior RH as a function of air changes per hour and moisture production rates.

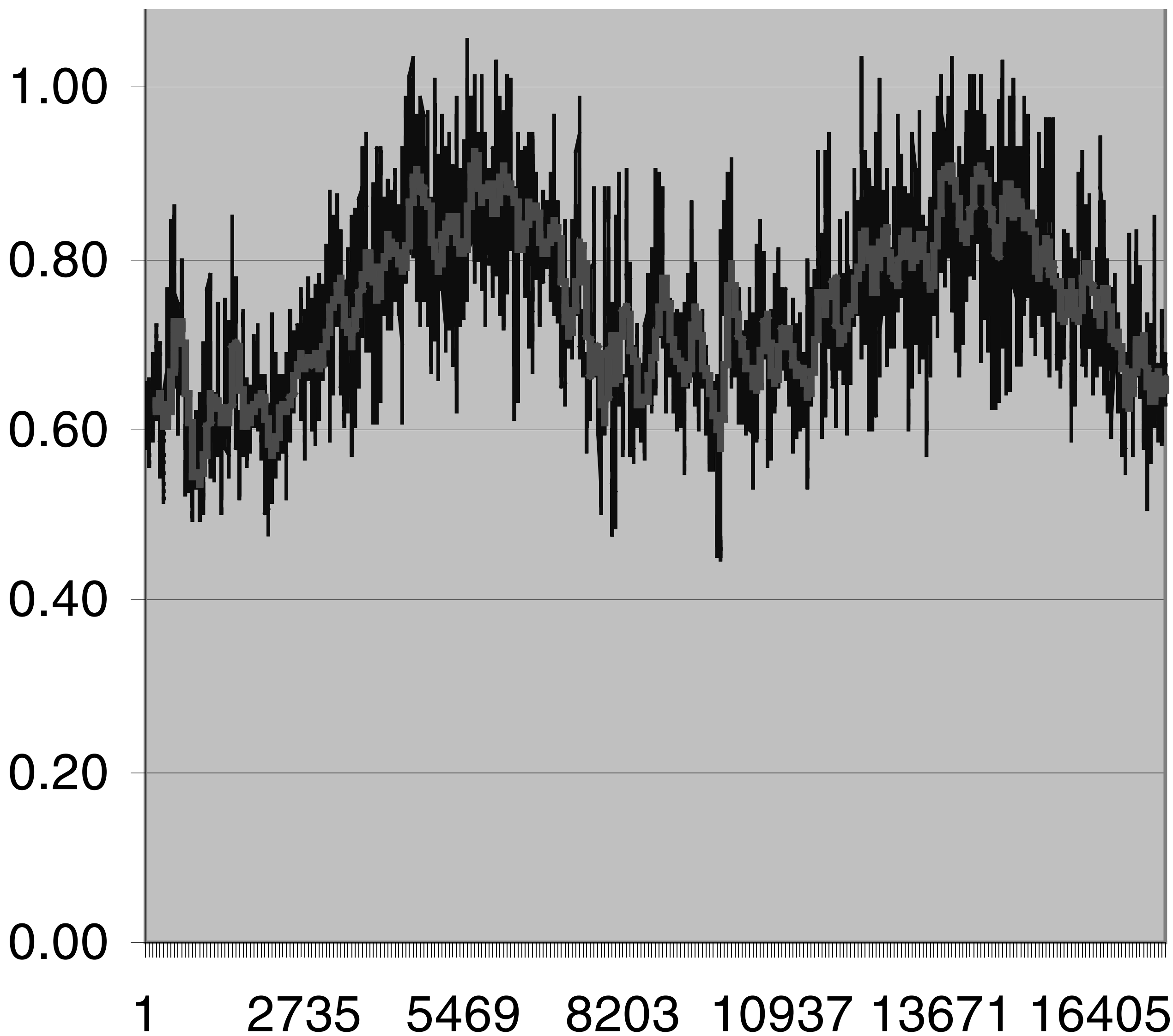

Fig. C18. Seattle interior RH with T=21 C, moisture production 10 kg/day, ACH=0.3,area= 80 m^2.

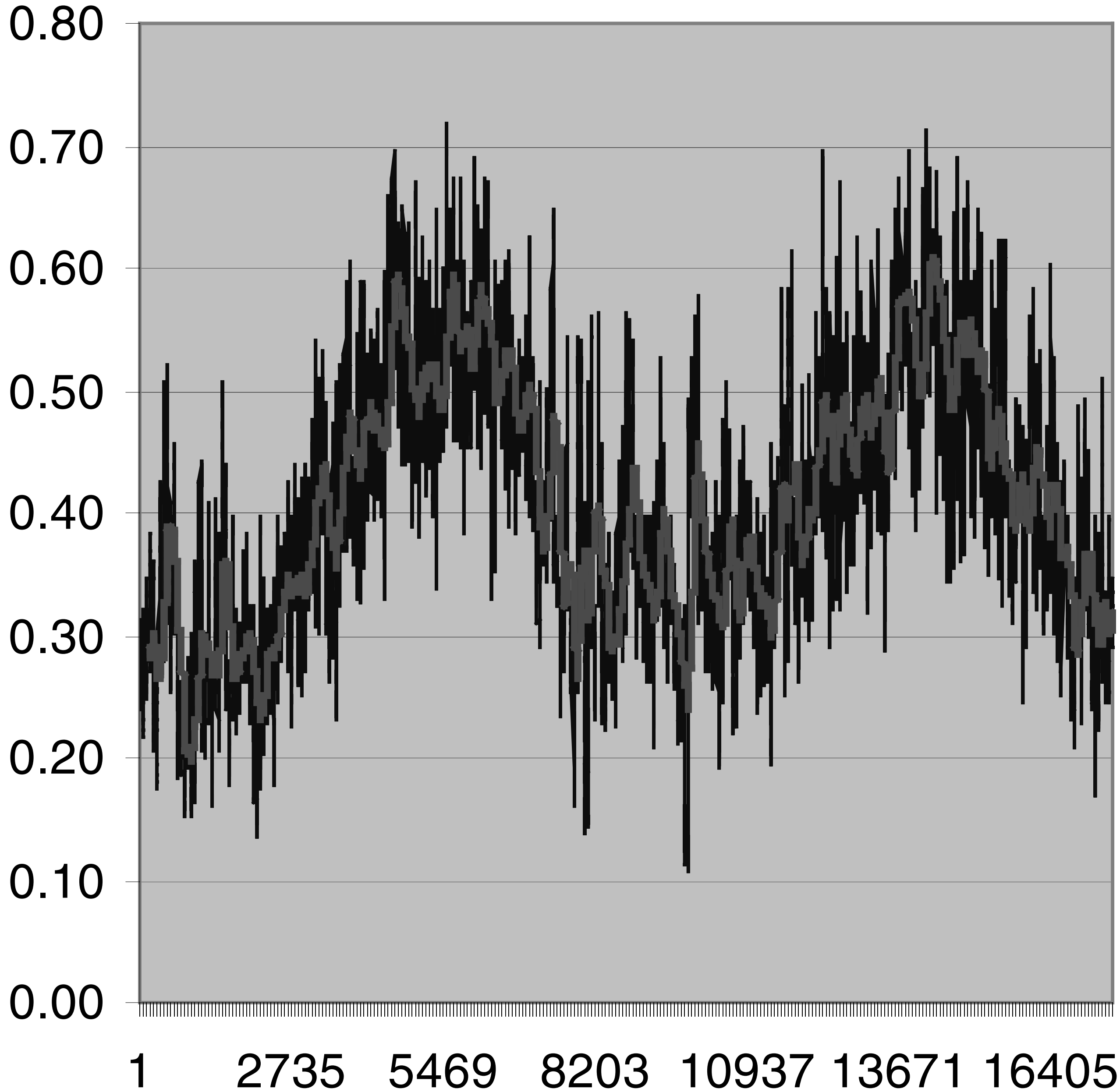

Fig. C19. Seattle interior RH with T=21 C, moisture production 10 kg/day, ACH=3, area= 80 m^2.

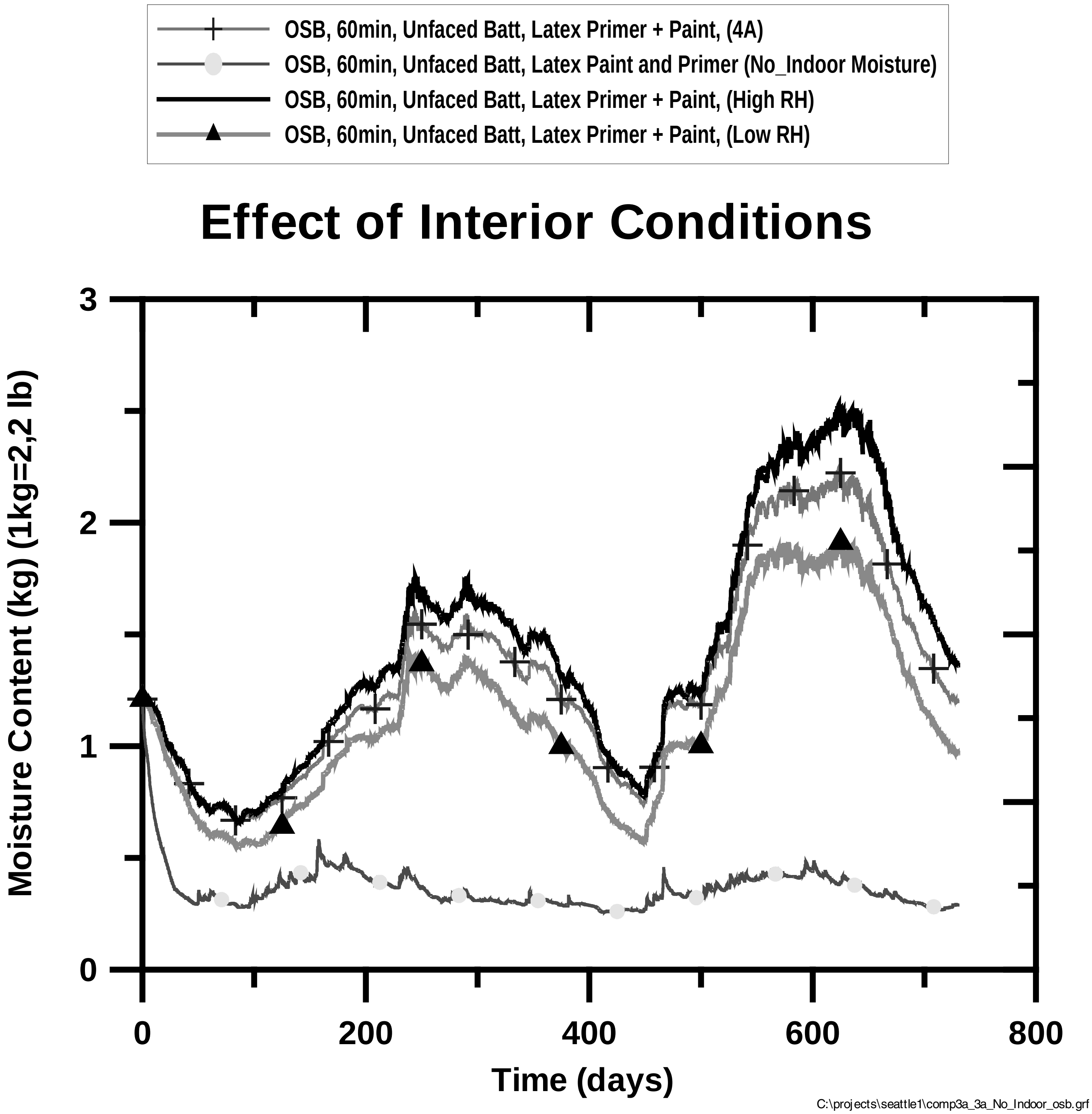

Fig. C20. Effect of interior RH on OSB sheathing board (wall 4A).

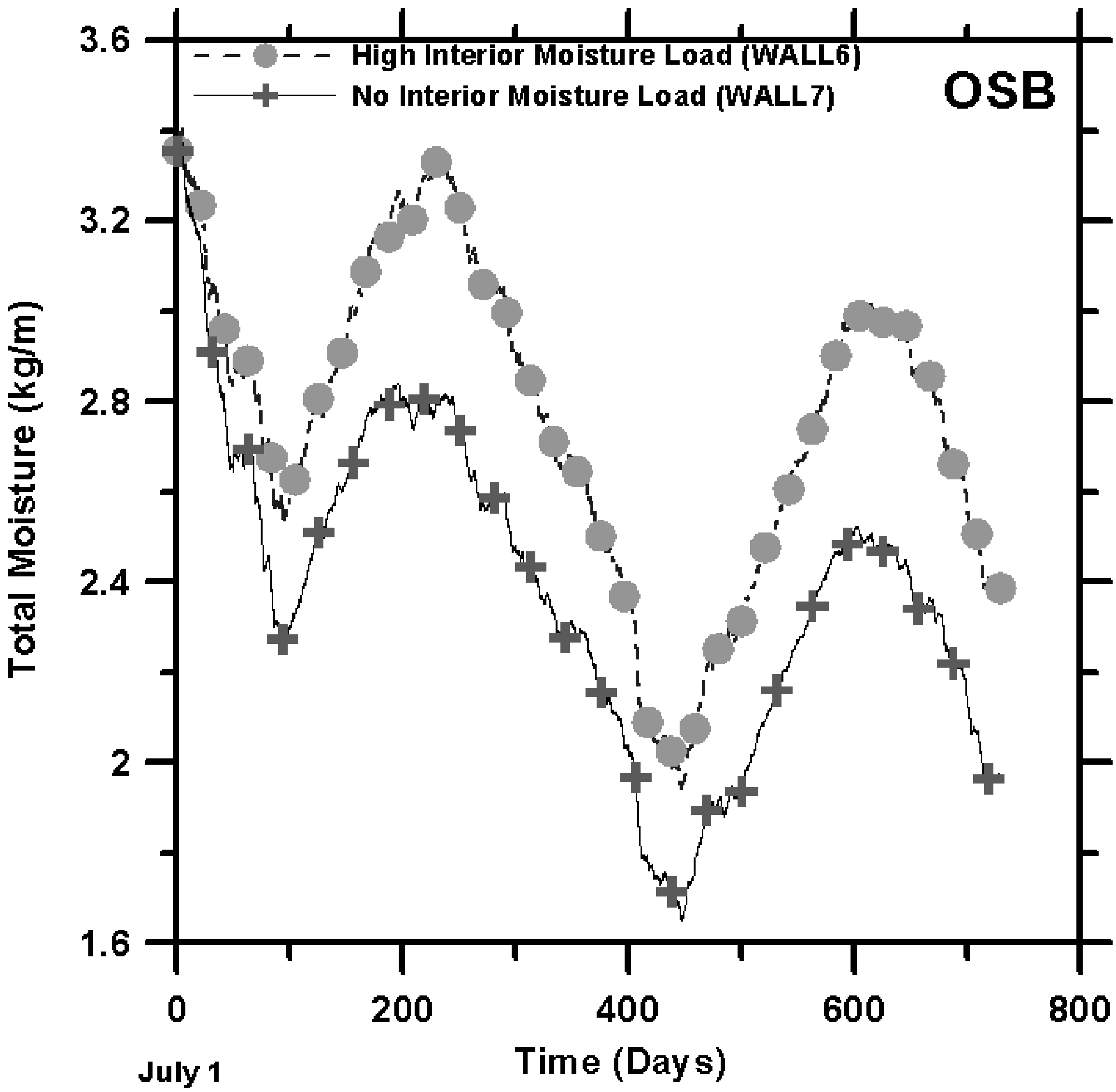

Fig. C21. Total moisture content as a function of time. Two different levels of interior relative humidity environments, one high load and the other no moisture production**.**

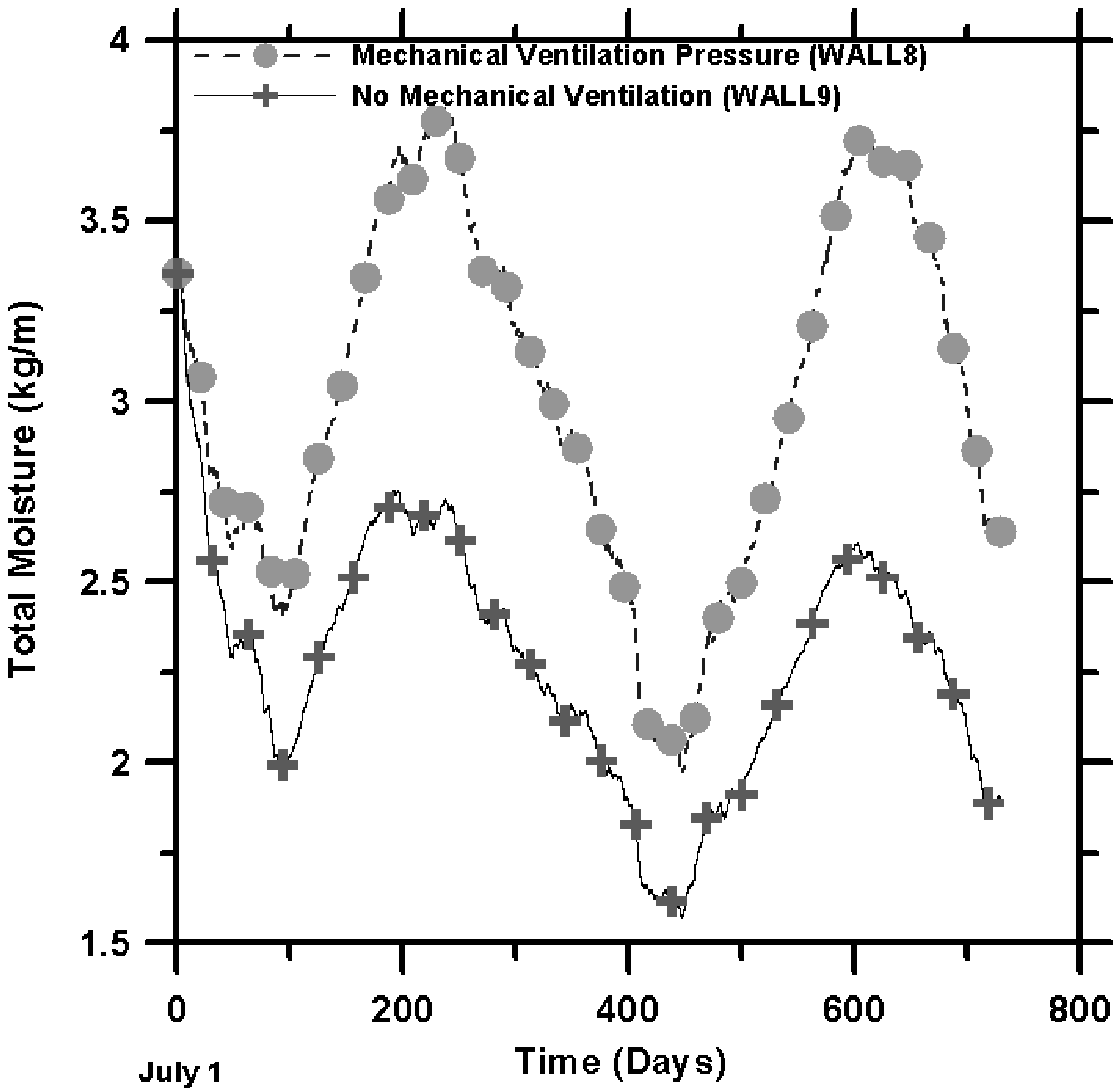

Fig. C22. Effect of mechanical ventilation on moisture accumulation in OSB.

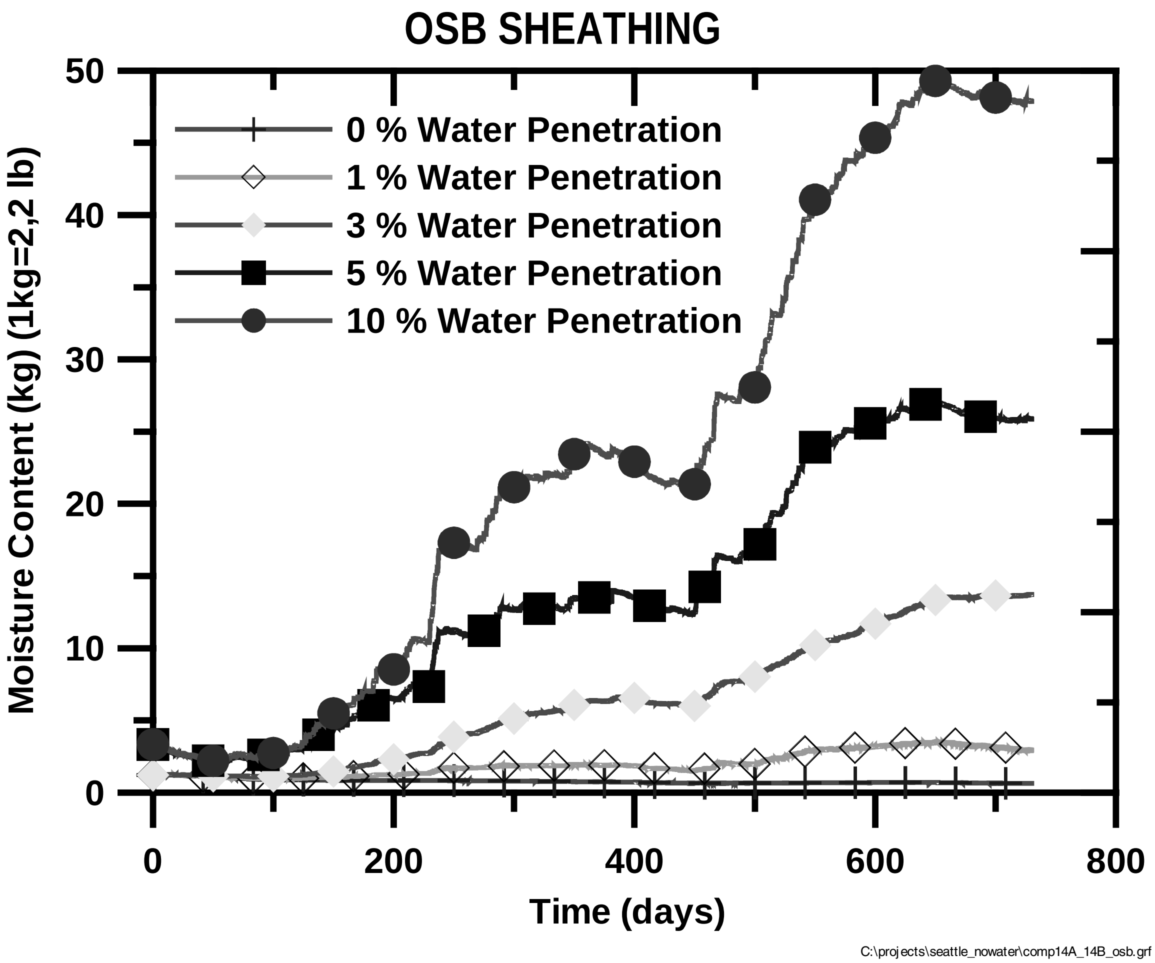

Fig. C23. Influence of water penetration on OSB performance.

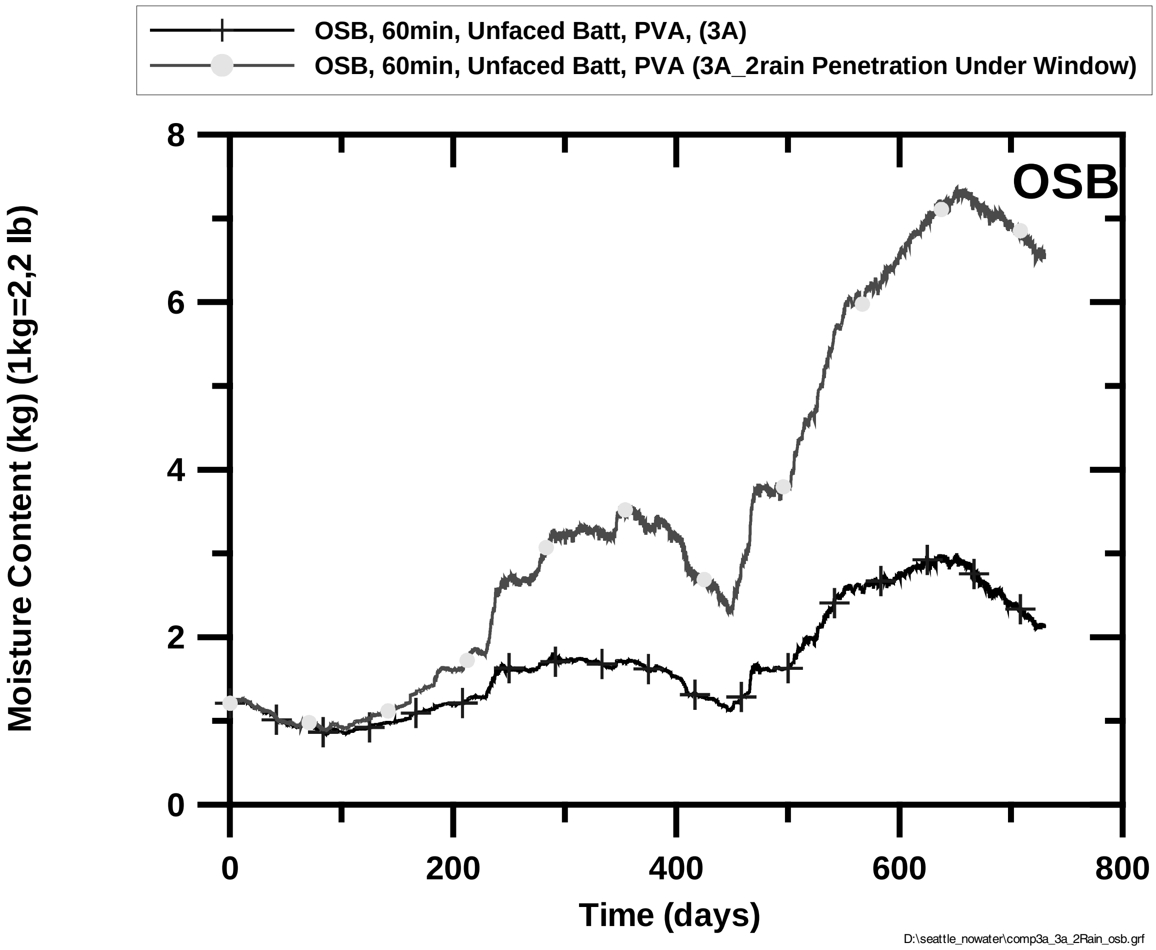

Fig. C24. Influence of water penetration on OSB performance.

Pre-84 Stucco and Cedar Siding

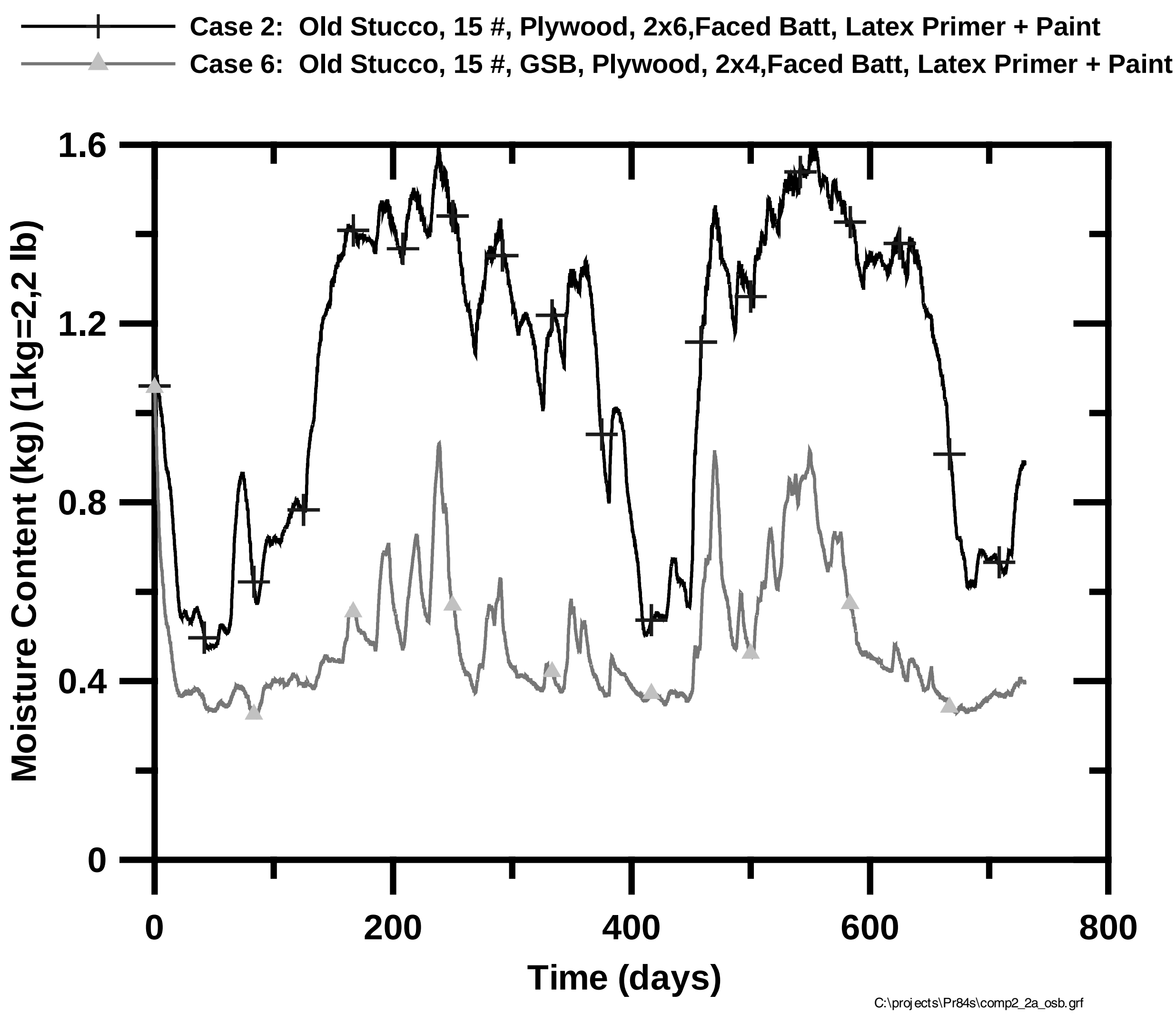

Fig. C25. Comparison of plywood moisture content of stucco-clad systems wall 2 and 6 (pre-1984).

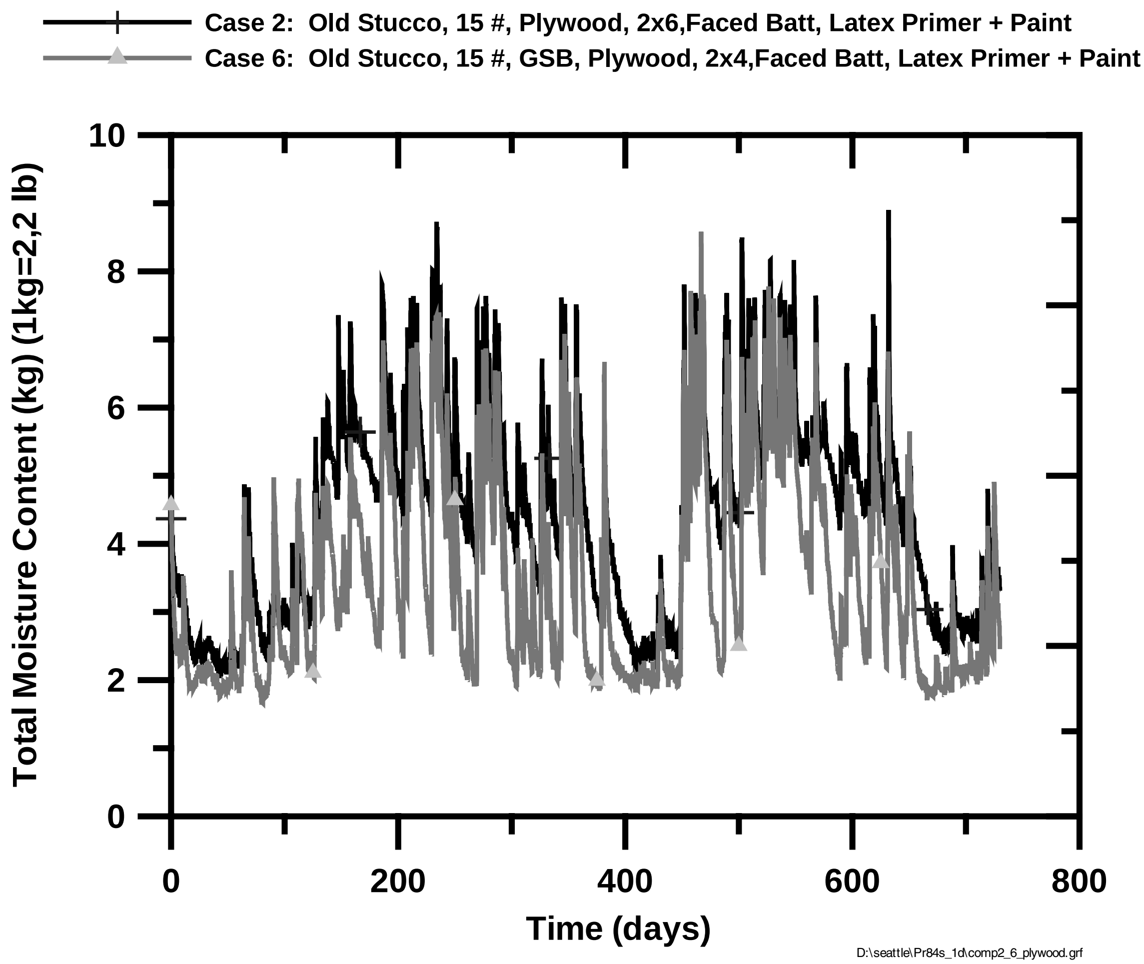

Fig. C26. Comparison of total moisture content of stucco-clad systems wall 2 and 6 (pre-1984).

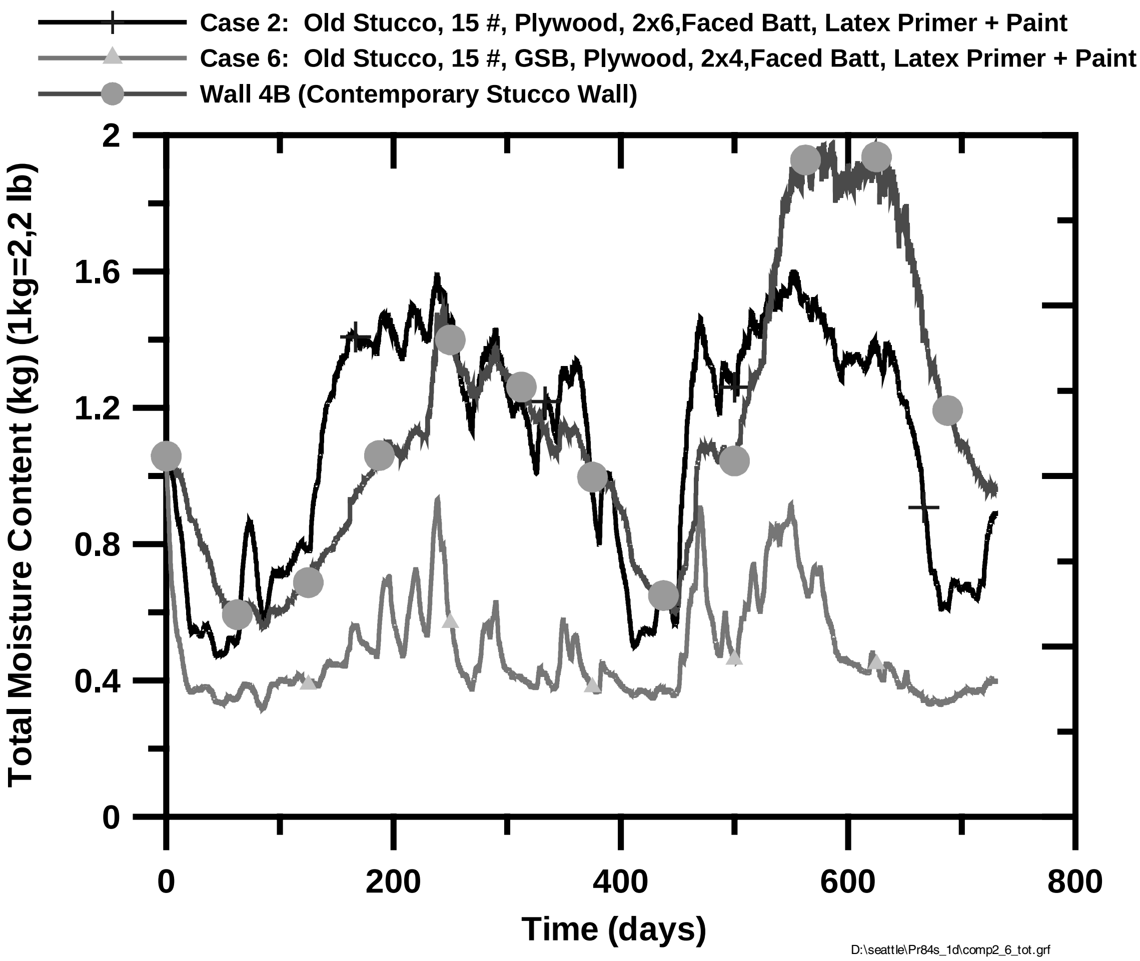

Fig. C27. Comparison of total moisture content of stucco-clad systems wall 2 and 6 (pre-1984) and wall 4B.

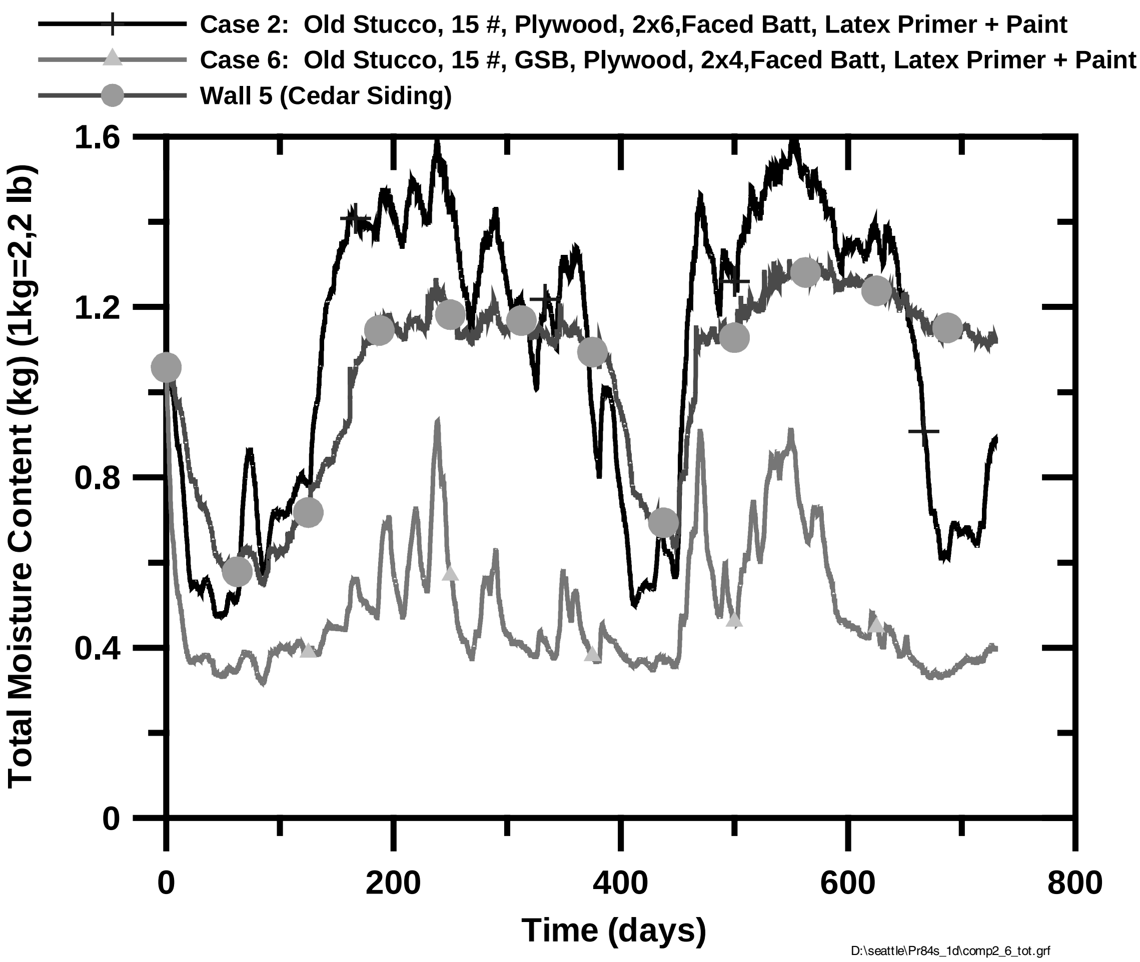

Fig. C28. Comparison of total moisture content of stucco-clad systems wall 2 and 6 (pre-1984) and a cedar-clad wall 5.

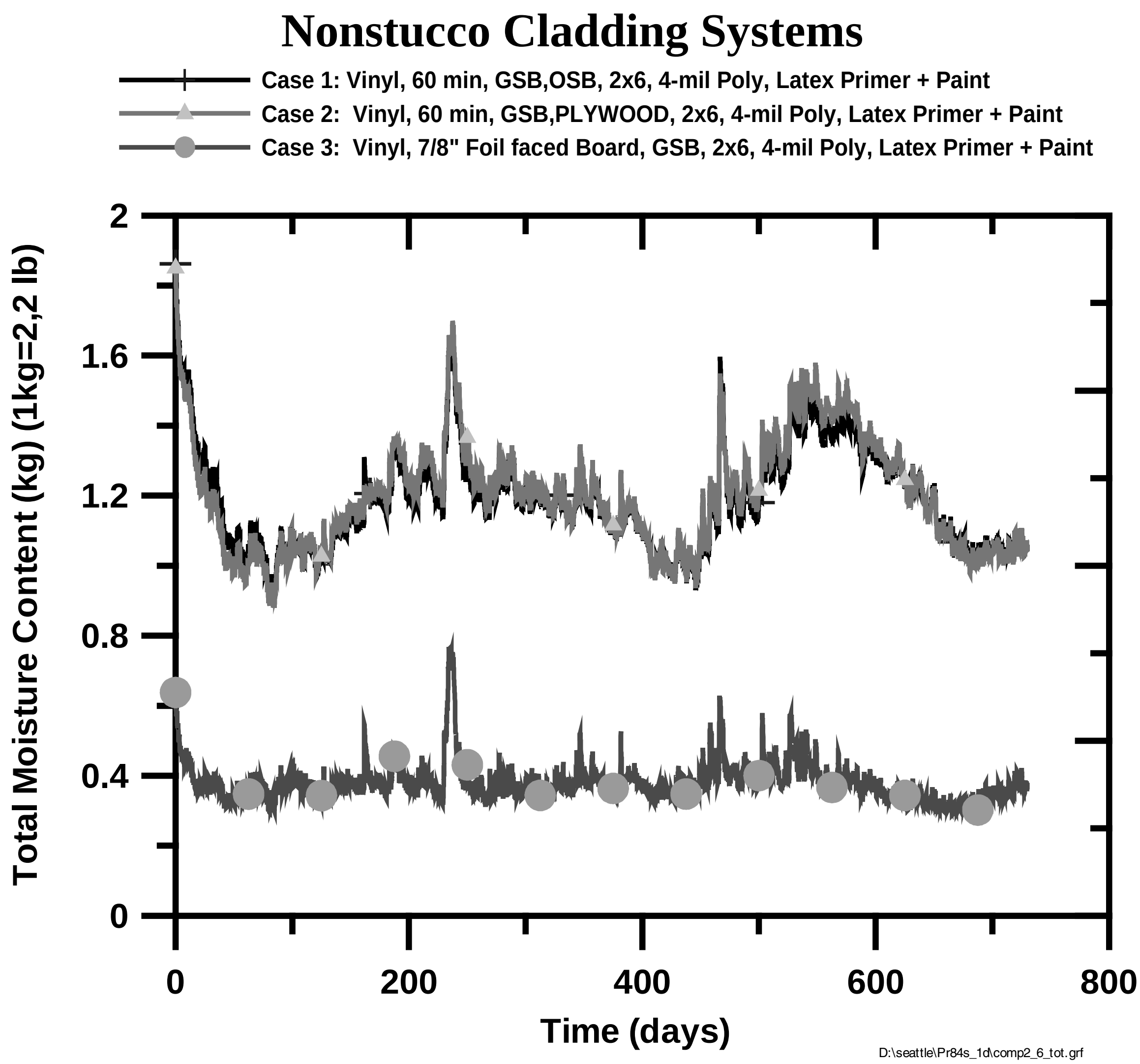

Fig. C29. Comparison of total moisture content of nonstucco contemporary walls (1, 2, and 3).

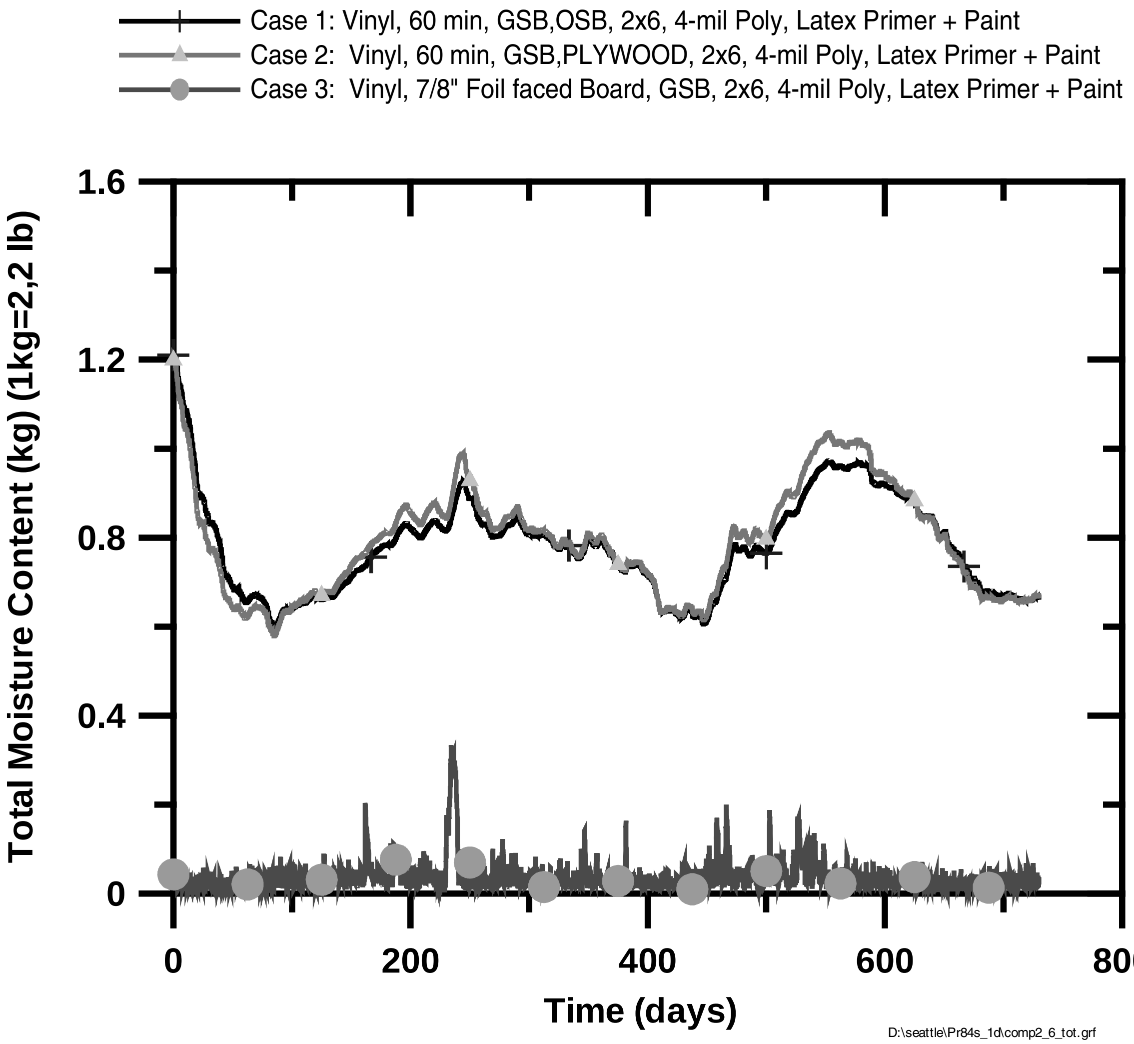

Fig. C30. Comparison of total moisture content of nonstucco contemporary walls (1, 2, and 3).

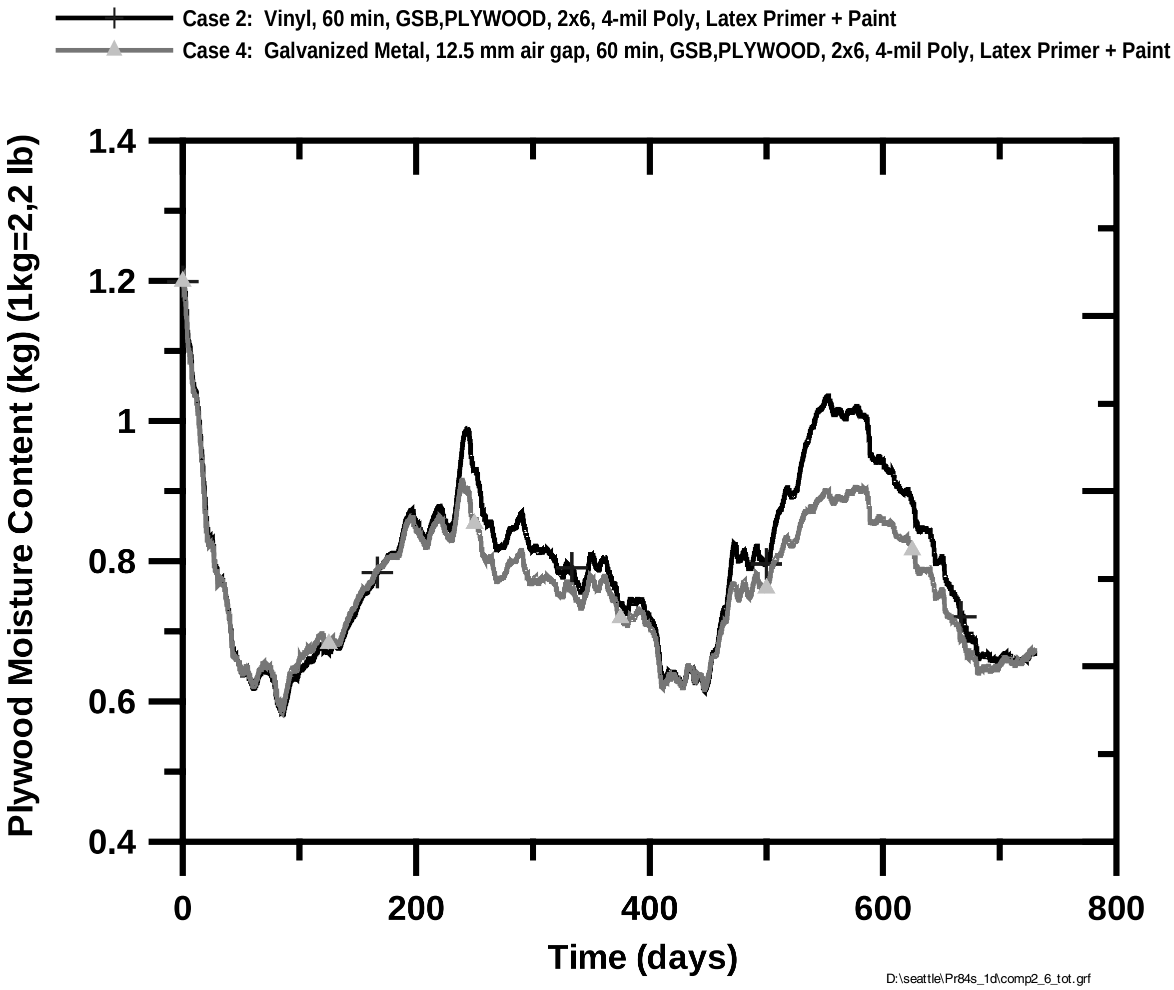

Fig. C31. Comparison of plywood moisture content of nonstucco contemporary walls (2 and 4).

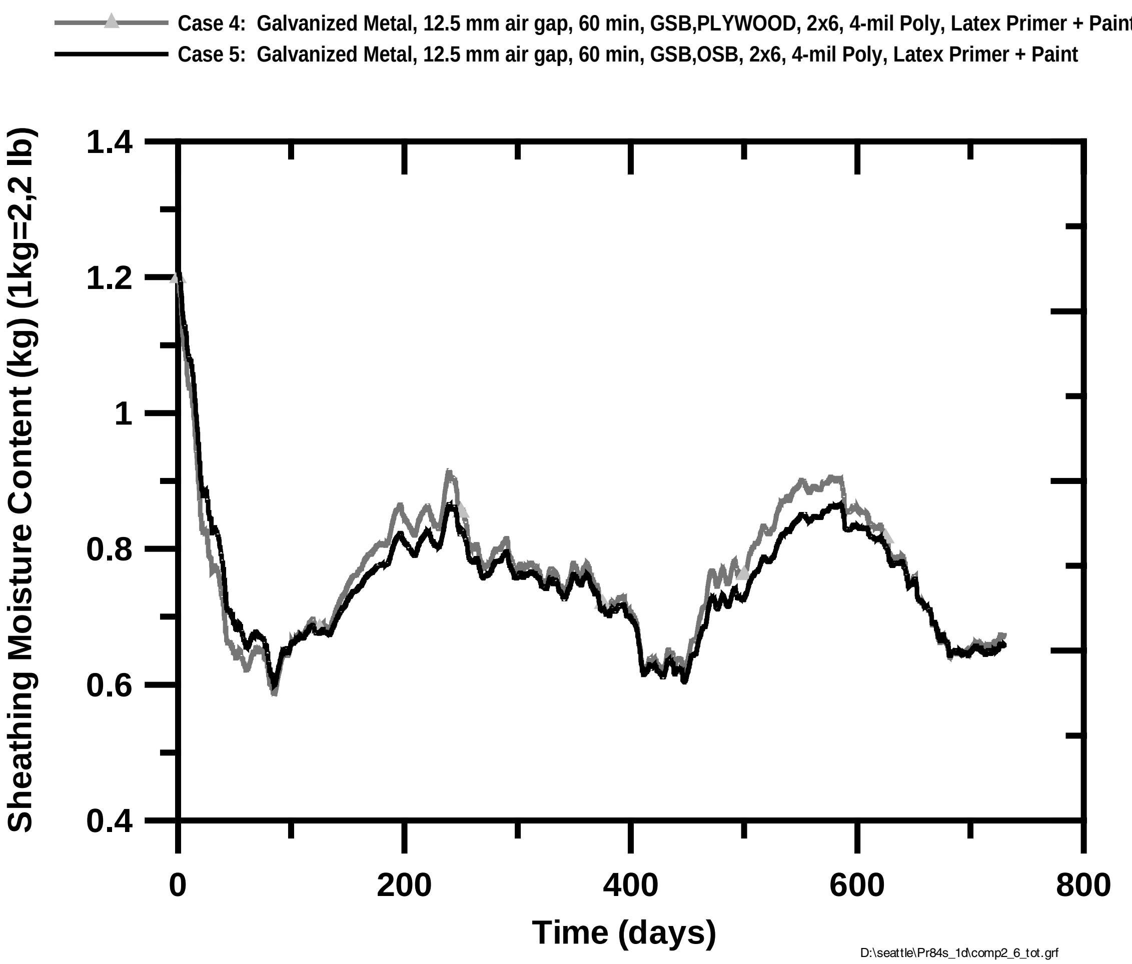

Fig. C32. Comparison of plywood moisture content of nonstucco contemporary walls (2 and 4).

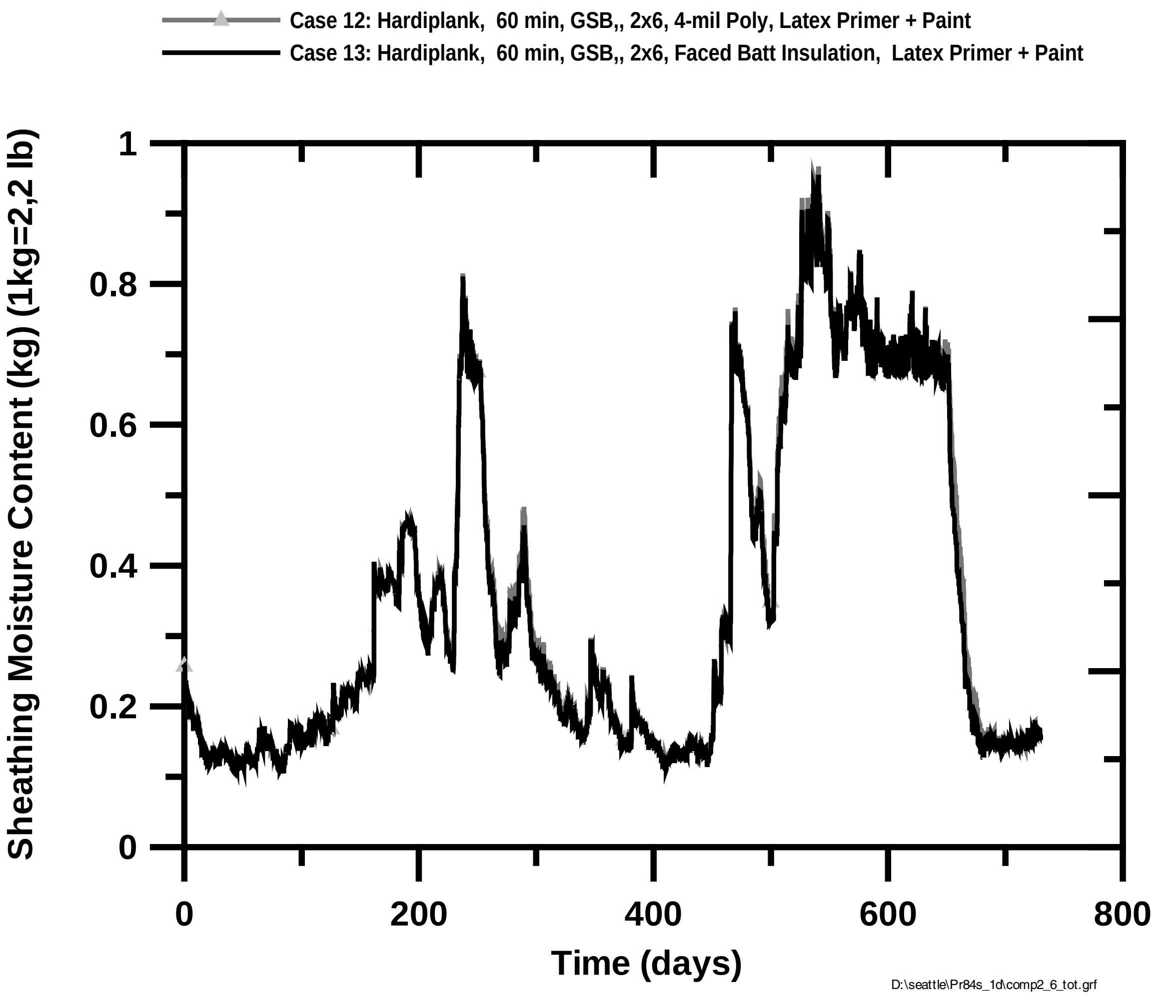

Fig. C33. Comparison of GSB moisture content of nonstucco contemporary walls (12 and 13).

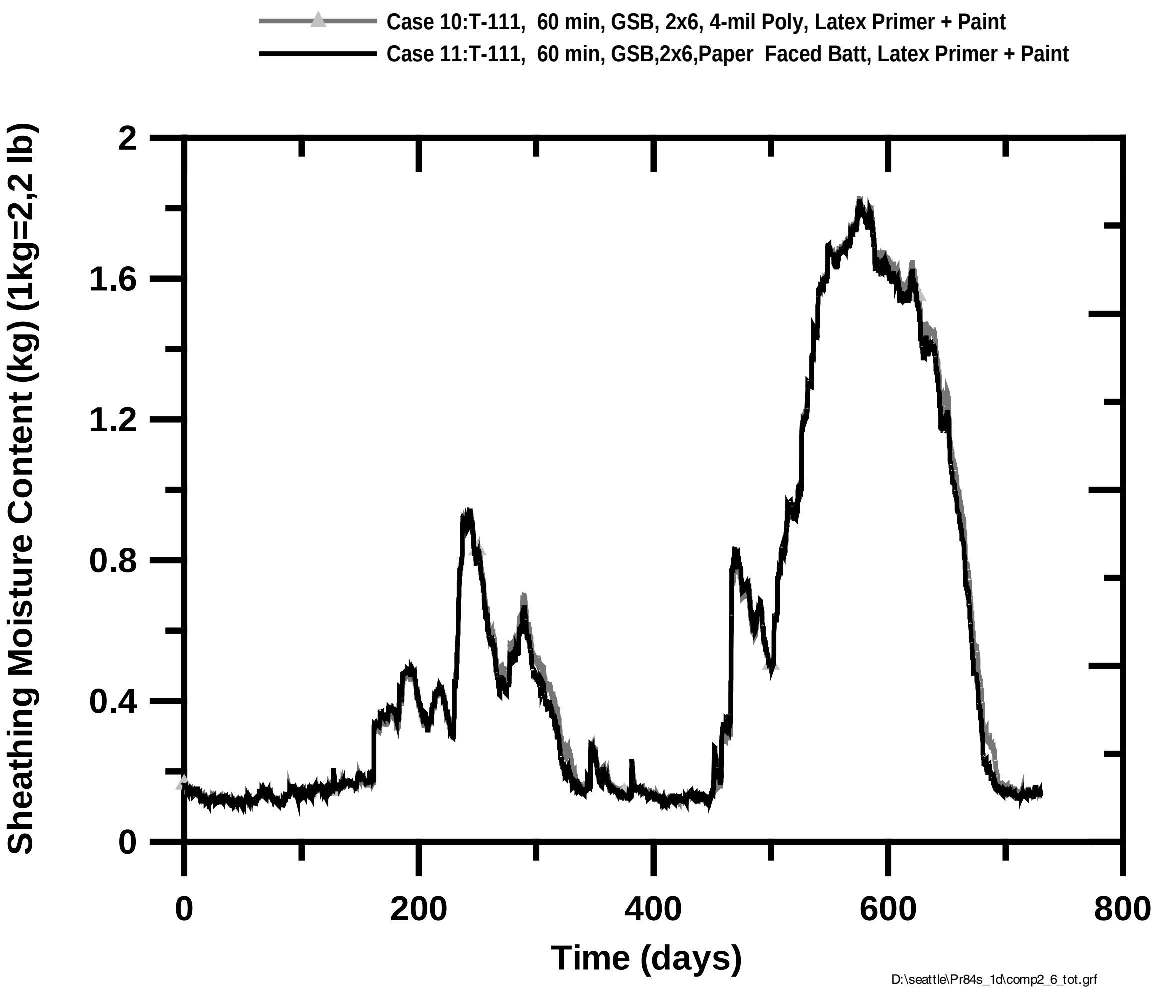

Fig. C34. Comparison of GSB moisture content of nonstucco contemporary walls (10 and 11).

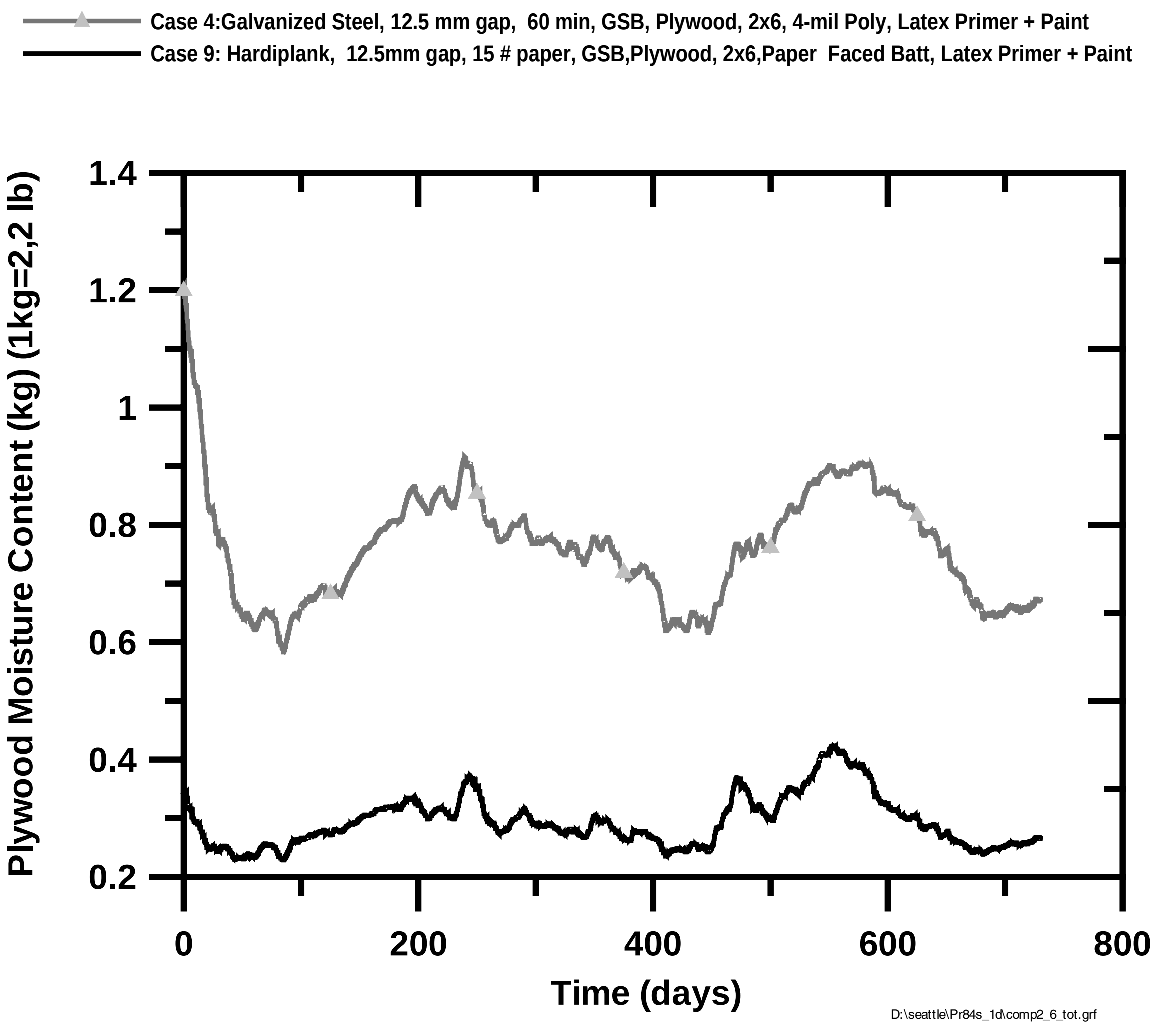

Fig. C35. Comparison of GSB moisture content of nonstucco contemporary walls (4 and 9).

APPENDIX D

PRELIMINARY INVESTIGATION OF DRAINAGE IN FULL-SCALE WALLS CLAD WITH STUCCO AND HORIZONTAL VINYL SIDING

Submitted by Achilles Karagiozis
to
The Seattle Department of Design, Construction and Land Use (DCLU)
and the Moisture Damage Committee

In compliance with the City of Seattle
Department of Design, Construction and Land Use
Building Enclosure Hygrothermal Performance Study

OAK RIDGE NATIONAL LABORATORY
STATE PARTNERSHIP PROGRAM
JJAC TEST HOUSE REPORT

Test and report prepared by:

John Straube
Joe Lstiburek,
Achilles Karagiozis
Chris Schumacher, JJAC

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INTRODUCTION

Drained wall systems, or rainscreens, are widely believed to provide better resistance to rain penetration. Drainage in wall systems with defined air spaces is clearly excellent—the drainage provided by small gaps, opening and cracks that naturally form between layers of cladding and sheathing membranes has not been explored.

A simple test program was devised by Drs. Joe Lstiburek, Achilles Karagiozis, John Straube, and Mr. Chris Schumacher to investigate drainage in full-scale walls clad with stucco and horizontal vinyl siding.

TEST HOUSE DESCRIPTION AND CONSTRUCTION DETAILS

An octagonal test house, comprising eight 4-ft-wide and 8-ft-high 2×4 framed walls, was constructed on the site of Building Sciences Corporation offices in Westford, MA, during the weekend of July 31–August 2, 2000 (see Figs. 1–6). The eight walls comprised seven test panels and one door.

Fig. 1. Octagon base of the test hut.

Fig. 2. Construction and nail detailing of the base of the octagon.

Fig. 3. Final touches to provide necessary support of the base of the octagon test hut.

Fig. 4. Approval/certification of the octagon test hut base.

Fig. 5. Exterior sheathing with designed visual openings.

Fig. 6. Designed visual openings in wall segment.

Fig. 7. Materials for hut—Lousiana Pacific OSB panels.

Fig. 8. Materials for hut—asphalt felt.

ASSEMBLED TEST HUT

To allow for the observation of the presence and movement of water, view ports were provided through the sheathing in walls with sheathing and a weather barrier (see Fig. 9). These ports were 10 in. x 10 in. located in the middle of each stud space, 20 in. from the top and bottom, for a total of six per panel. The sheathing was installed in two pieces so that a full-width ¾-in. gap existed at midheight. Paper could be inserted between the sheathing and sheathing membrane at view ports to check for the presence of liquid water during pressure tests.

Holes were cut through the water resistive barriers at several of the view ports on each panel to allow for inspection of the back of the cladding and to provide visible evidence of drainage.

Fig. 9. Inside view of test house with closed view ports visible.

VINYL CLADDING TESTS

The test panels were sheathed with a variety of common materials and all were clad with a double-four vinyl siding (see Table 1). The siding was installed according to manufacturers recommendations, with a gap of approximately ½ in. between the end of the siding and the end of the vertical J-trim. Vertical joints were staggered over the height with one vertical joint every third course.

Table 1. Vinyl-clad test walls

Panel	Sheathing Membrane	Sheathing
1	None	$^{7}/_{16}$ in. OSB
2	No. 15 felt	$^{7}/_{16}$ in. OSB
3	Tyvek HouseWrap	$^{7}/_{16}$ in. OSB
4	Tyvek HouseWrap	$^{7}/_{16}$ in. asphalt fiberboard
5	None	$^{7}/_{16}$ in asphalt fiberboard
6	None	None
7	None	Thermoply

Test Methods

There are no appropriate standard test protocols for drainage behind cladding. Therefore, some ad hoc testing was conducted to develop and validate test protocols.

Method A

Water was applied to the face of the siding with a spray from a garden house equipped with a shower nozzle. This water was applied to panel 1 [vinyl over oriented strand board (OSB)] for 8 min. Water was observed flowing in the vertical J-trim edges and laterally along the vinyl profile after about
3 min. The water in the horizontal reveal of the siding never extended more than 4 in. from the edges since drainage to the edges was constantly occurring.

Method B

Because of the lack of visible water penetration and the likely variability of water penetration between panels, a second method was developed. A measured quantity of water was poured from a 4-L container and directed behind the vinyl siding by means of a reverse window head flashing (Figs. 10 and 11). Ten liters of water (measured) was applied to panel 1 (OSB only) over a time period of approximately 5 min. Water ran vertically between the back of the vinyl and the face of the OSB. At horizontal obstructions created by the back of the vinyl siding, some water was captured by the vinyl profile and drained laterally in the profile to the J-trim. The remainder continued downward. Much of the water was drained laterally in the top half of the panel. No water was observed in the lower view ports or OSB horizontal joint at midheight.

Test Observations

Method B was applied to all of the remaining panels. Water could be seen running on the outside of the Tyvek through the view ports in Tyvek/OSB and Tyvek/fiberboard panels. No water was seen to penetrate. It is assumed the panels with No.15 felt paper performed in the same manner. No water was seen penetrating through walls with only fiberboard, XPS, or thermoply.

The walls were opened after testing, and in the majority of the walls the sheathing membrane or sheathing was dry, but the back of the vinyl was often wet (beaded water). The walls with dry drainage planes included panels 1, 2, 3, 4, 5. Panels 6 and 7 had water on the XPS and cardboard respectively. We hypothesized that water flowed differently behind nonflat surfaces. The XPS was wavy, and so was Ener-G Brace, so water could be trapped here, not within the vinyl.

Method A/50 Pa. Using a blower door and manometer, a 50-Pa inward pressure was applied to the test house. Water was applied with the garden hose/shower head technique. Water was observed to leak inward at the edges of the J-trim. The horizontal profile slowly filled over the first 2 min. At this time, water began to overflow the channels in the vinyl. Some water collected from the field of the wall, presumably from the vertical joints in the siding (one of which was located directly above a view port). The test was stopped after 5 min.

Fig. 10. Water being applied to top of panel.

Method A/50 Pa was applied to panel 3 (Tyvek over OSB). No water was visible after 5 min.

Method B/50 Pa was applied to panel 3. No water was visible after 5 min.

Method A/100 Pa was applied to panel 3. About ½ teaspoon of water was observed in the upper right view port after 5 min. Some drips of water were seen between the two top plates.

Method B/100 Pa

- Panel 3. Same leak was observed as in the previous test.
- Panel 7. After 6 L of water, a leak develop as a small stream of water at the vertical joint. This leak continued as the remaining 4 L of water was applied.
- Panel 6 (XPS). After the first 4 L was applied, a leak developed as a single stream of water from the lowest horizontal joint. As the remainder of water was applied, this leak became stronger and evolved into three streams of water.
- Panel 5 (fiberboard). No visible leaks were observed.
- Panel 2 (No. 15 OSB). A dripping leak formed at a defect (small checks) in the paper, visible in the view port. These small defects were noted during construction as well.

Method B/150 Pa was applied to panel 3. Old leaks from previous testing did not occur. A new leak was visible at the midheight gap.

Fig. 11. Water poured behind vinyl at top can be seen emerging and draining on outer face.

Discussion of Vinyl Results

Observations led to the following conclusions about vinyl:

1. Water applied to the face of the vinyl leaks predominately through the J-trim and probably to a lesser extent, through the vertical joints. Applying a pressure difference inhibited drainage of the horizontal profile and thus increased the amount of water dumped on the drainage plane.

2. Water applied behind the vinyl is quickly redirected to the horizontal profile of the siding and carried to the vertical J-trim where it is drained downward.

3. The majority of the water applied in both test methods did not contact significant areas of the drainage plane. This may or may not represent performance in a real building environment.

4. Vertical lap joints in structural cardboard and horizontal joints in XPS are prone to leakage under pressure differences of 100 Pa or greater.

STUCCO-CLADDING TESTS

The test panels were sheathed with a variety of common materials, and all were finished with a standard three-coat stucco system about ¾–$^{7}/_{8}$ in. thick. The stucco was left unpainted. Stucco lath was attached with lathing nails through the sheathing membrane, if present. Each of the seven panels is described in Table 2.

Table 2. Stucco-clad test walls

Panel	Sheathing membrane	Sheathing
1	No. 15 felt	$^{7}/_{16}$ in. OSB
2	No. 15 felt + StuccoWrap	$^{7}/_{16}$ in. OSB
3	StuccoWrap	$^{7}/_{16}$ in. OSB
4	Tyvek HouseWrap	$^{7}/_{16}$ in. OSB
5	No. 30 felt	$^{7}/_{16}$ in. asphalt fiberboard
6	Grade D 60 min + Grade D 60 min	None
7	No. 15 felt + No. 15 felt	$^{7}/_{16}$ in. OSB

Test Methods

Because of the likely limited amount of water penetration through the crack-free quality stucco, and the likely variability of water penetration between different stucco panels, the same test method used for the vinyl tests was used for the stucco tests. A measured quantity of water was poured from a 2-L container and directed behind stucco by means of a reverse window head flashing (Fig. 12) with end dams. Typically, 2 to 4 L of water (measured) was applied to the trough formed by the head flashing. After water was seen running between the stucco and the outer layer of sheathing membrane, water was poured between layers of any two-layered sheathing membranes using the same 2-L container.

Test Observations

Water applied to the trough usually caused wetting of the stucco and local drainage at the metal J-trim first. It would often take some time for the water to drain to the bottom of the stucco panel, but it always occurred at the edges first. The use of peel-and-stick end dams on the troughs reduced the amount of water that bypassed the panel, but never eliminated it. Panels eventually showed drainage through the middle of the panel, but this could take a long time and could be only a few drops.

In all cases, water was seen to drain almost exclusively through the grooves left in the back of the stucco by the stucco lath. Water ran slowly down these diamond shaped grooves. In locations where the sheathing membrane was adhered or the stucco was smoothly “cast,” drainage did not seem to occur.

The SBPO products were observed to adhere to the stucco rather well, and needed to be “torn” off the stucco with a knife and considerable hand pressure. The StuccoWrap was somewhat easier to remove than the HomeWrap, but not much. The felts adhered to the stucco nearly as well. The grade D paper adhered the least, but it definitely did adhere.

The grade D paper and the No. 30 fiberboard panel both exhibited some bleed though of the asphalt. Painting the surface may alleviate this as a problem, but it is an interesting phenomenon.

Stucco Panel-Specific Observations

Panel 6 Most drainage occurred between stucco and outer layer—about 6 L in 5 min, because grade D paper bonded to the stucco the least. No penetration to the second layer was seen. Water drained between layers almost as fast as it was poured, approximately 2 L in 10 s.

Panel 1 After about 1000 mL had been applied, water was seen on the back of the stucco on the right hand top view port. Water poured between the layers of building paper drained very quickly (1 L in less than 30 s).

Panel 2 Water applied between layers drained very fast. Water was first applied between stucco and paper and was appeared between the building paper and the StuccoWrap after less than 500 mL. It is presumed that water passed through the No.15 felt paper because of some of the small holes (assumed to be defects) in the paper. It may have been through nail holes, but we do not know. Water was not seen between the paper and the stucco until 2 L of water had been applied. Water applied directly between the two layers of a weather-resistive barrier (WRB) was seen draining immediately and as quickly as it could reasonably be applied.

Panel 7: Slow drainage occurred between stucco and No.15 paper, likely because of the observed bonding, but excellent drainage between layers occurred—just as good as in panels 1,2, and 6 (see Fig. 13 and 14).

None of the remaining panels provided good drainage. All had slow drainage (e.g., as much as 10 min for 0.5 L.

Panel 3: Slow drainage occurred—about 2 L over 5 min. Water applied to trough drained very slowly. Stucco was bonded to StuccoWrap well enough that lettering was transferred. Some water was seen between stucco and wrap after 2 L were applied slowly, but this appeared near the vertical edge and may have bypassed some of the bonded areas. The water drained through rough, nonbonded areas as in the other panels.

Panel 5: Slow drainage occurred with extensive bonding of the paper to the stucco.

Panel 4: Water drained very slowly from trough. Fibers were pulled from face of the HomeWrap by bonding. No water was seen to drain in front of the Tyvek (Fig. 15

).

Fig. 12. Water behind stucco drained through gaps and spaces left by lath.

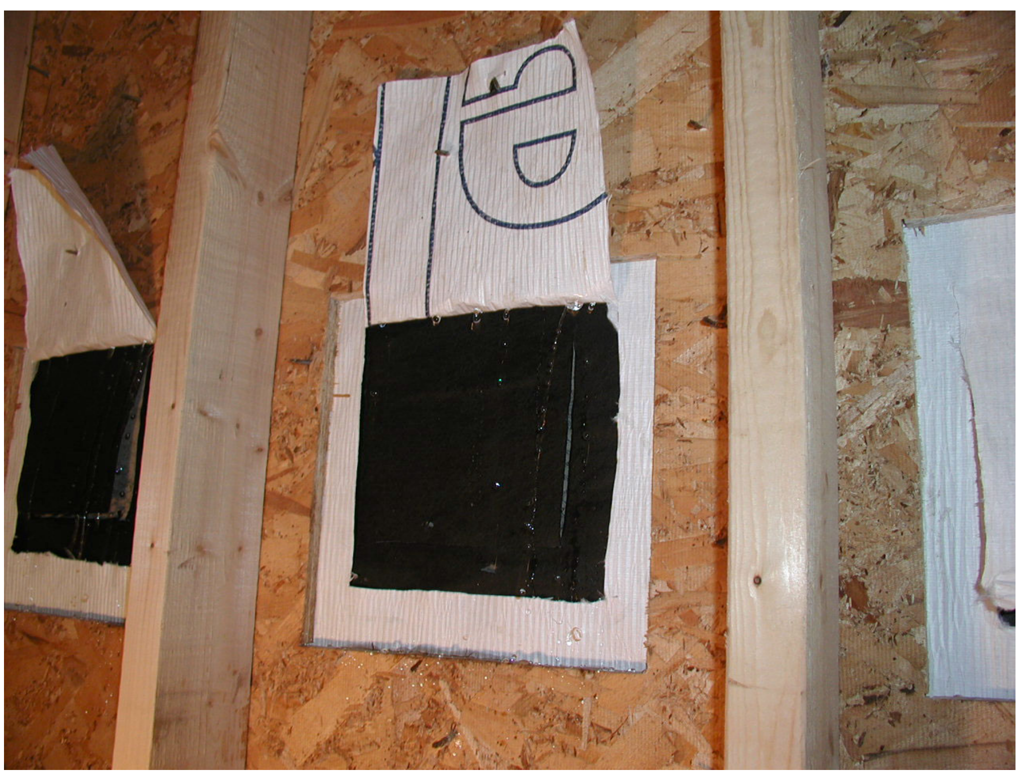

Fig. 13. Mulitple layers allowed excellent drainage.

Fig. 14. Another mulitlayer wall exhibiting excellent drainage.

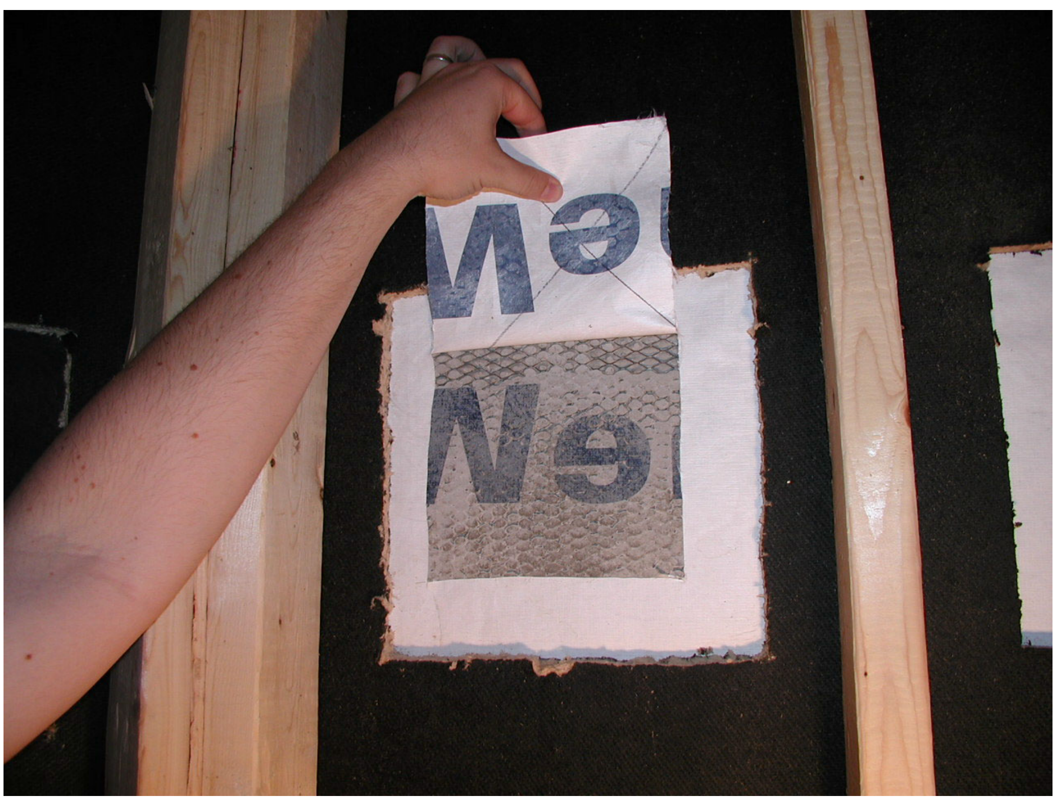

Fig. 15. Tyvek adhered well to stucco.

Discussion of Stucco Results

Observations led to the following conclusions about stucco:

1. Building papers, felts, and polymer-based house wraps all can adhere to the back of the stucco cladding, but paper adheres the least well, and polymer-based adheres best.

2. The greater the area of bonding, the less water could drain. The provision of a second layer of building paper ensured a gap without bonding, and thus resulted in excellent drainage in this layer.

3. Single layers of sheathing membrane may control water penetration, but this likely occurs only because it acts as a perfect barrier, not because it allows drainage. Even the corrugated polymer-based house wrap did not allow any significant drainage. The same corrugated house wrap over building paper drained very well.

APPENDIX: DETAILED DESCRIPTION OF TEST PANEL MATERIALS

- No. 15 saturated felt—North Eastern Saturated Felt Co.
- 7/16” OSB—Louisiana Pacific
- StuccoWrap by Dupont (stapled)
- SBPO—Tyvek HouseWrap
- 7/16-in. Fiberboard—BPCO High Density
- No.30 saturated felt—Tarco Inc, Belton, Texas
- Grade D, 60-min paper—Fortifiber Fortify
- No sheathing
- Vinyl siding—Home Depot